NTIA Report 15-518

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report series

U.S. DEPARTMENT OF COMMERCE • National Telecommunications and Information Administration

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ABBREVIATIONS/ACRONYMS

BRAN	Boulder Research and Administration Network
CEC	Coors Event Center
CINR	Carrier to interference-plus-noise ratio
COTS	Commercial off the shelf
COW	Cell on wheels
CRADA	Cooperative Research and Development Agreement
DAS	Distributed antenna system
DHS-OIC	Department of Homeland Security Office of Interoperability and Compatibility
DLC	Discovery Learning Center
eNB	Evolved Node B (LTE base station)
EPC	Evolved packet core
FOS	Facilities and offices section of the Coors Event Center
GUI	Graphical user interface
ITP	Interdisciplinary Telecommunications Program (University of Colorado)
LTE	Long Term Evolution
MM	Multi-mode
NCAR	National Center for Atmosperic Research
PDSCH	Physical downlink shared channel
PSCR	Public Safety Communications Research program
PSCR MN	PSCR Macro Network
PUSCH	Physical uplink shared channel
RSRP	Reference signal received power
SCDA	Small cell feeding discrete antennas
SCDAS	Small cell feeding a distributed antenna system

SM Single-mode

TCP Transmission control protocol

UDP User datagram protocol

UE User equipment (LTE modem used in the testing)

USB Universal Serial Bus

IN-BUILDING LTE TESTING AT THE UNIVERSITY OF COLORADO

Bob Johnk,[1] Mitchell Powell,[2] Jaydee Griffith,[1] Mark McFarland,[1] Ken Baker,[3] Prachee Daithanker,[3] Saman Samdian,[3] Lavanya Gopal,[3] Sai Gavva[3]

This report describes a comprehensive series of tests that were conducted by engineers and researchers from the U.S. Department of Commerce's Public Safety Communications Research (PSCR) program and the University of Colorado during the period of July 2013–May 2014. The report presents results obtained at two buildings located on the campus of the University of Colorado at Boulder. Indoor coverage was measured using the PSCR Band 14 LTE outdoor macro network. We also explored methods for improving in-building coverage using a cell on wheels and small cell feeding either discrete antennas or a distributed antenna system. The results indicate that the PSCR macro network by itself does not provide complete coverage inside these buildings and that coverage needs to be supplemented with combinations of a small cell deployed indoors and a cell on wheels (COW). The results indicate that significant system in-building performance improvements can be realized using small cells and a COW.

Keywords: antenna, backpack measurement system, Band 14, building, cell on wheels, channel analyzer, COW, indoor, LTE, macro network, modem, in-building, indoor propagation, signal, small cell, spectrum analyzer, test methods

1. INTRODUCTION

This report describes a comprehensive series of tests conducted by engineers and researchers from the U.S. Department of Commerce's Public Safety Communications Research (PSCR) program[4] and the University of Colorado during the period of July 2013–May 2014. The purpose of this work was to investigate both the in-building coverage characteristics of public safety Band 14 LTE systems and ways of improving indoor performance. In all the testing that we performed, a 10 MHz LTE bandwidth was used on both the downlink and uplink channels. The center frequencies of the downlink and uplink channels are 763 MHz and 793 MHz, respectively.

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1.1 Experiment Overview

Two measurement campaigns were conducted on the University of Colorado Boulder campus: the first at the Discovery Learning Center (DLC) and the second at the Coors Event Center (CEC). Both structures are well suited for such a study because they are located well within the coverage area of the PSCR Broadband Demonstration Network, an over-the-air macro network operated by PSCR in the public safety broadband spectrum (LTE Band Class 14). The PSCR demonstation network covers most of the city of Boulder, Colorado. The macro network was used as a baseline to study methods for improving indoor coverage.

We investigated three approaches for coverage improvement at the DLC: 1) a cell on wheels (COW) placed in close proximity to a building, 2) a small cell feeding two discrete antennas (SCDA), placed inside a building, and 3) a small cell feeding a distributed antenna system (SCDAS) installed in a section of a building. At the CEC, we did not deploy the SCDAS, and we used two coverage configurations based on a small cell feeding discrete commercial-off-the-shelf (COTS) antennas (SCDA) and a COW placed in an adjacent parking lot.

Our test results indicated that the PSCR macro network (PSCR MN) did not provide complete coverage of either the Discovery Learning Center or the Coors Event Center. We did see a significant improvement in indoor coverage and system performance when we used a small cell and COW individually or in combination. All in all, the report highlights the fact that the PSCR MN does not provide complete indoor coverage and that some form of in-building support is needed to achieve a high level of performance.

1.2 Structure of the Report

This report first describes the measurement campaign and results obtained at the DLC, then the measurements and results obtained at CEC. Over the course of the campaigns, our system measured a large number of LTE parameters for 6–8 different in-building coverage configurations. In addition, we performed separate measurements with both uplink and downlink data transmission using both transmission control protocol (TCP) and user datagram protocol (UDP) at the DLC and only UDP at the CEC. The number of data flow types and coverage configurations directly multiply the amount of data obtained. For instance, if we have 8 different coverage combinations and 4 different data flows, we have a multiplicative factor of 32 for the total amount of data obtained.

To provide a tractable presentation, we made three choices:

1) We focus on five key LTE parameters [1]-[4] that characterize the absolute signal level, signal-to-noise and interference, uplink and downlink data rate performance, and the transmit power levels of the LTE modem (also known as user equipment or UE):

   a) reference signal received power (RSRP)
   b) carrier and intereference to noise ratio (CINR),
   c) physical shared channel downlink data rate (PDSCH)
   d) physical shared channel uplink data rate (PUSCH)
   e) UE transmit power.

2) We present combined histogram plots of the LTE parameters for different in-building coverage types. This provides an effective side-by-side global comparisons of the types of in-building coverages.

3) We present data that is reported from the UE only since this will be of much greater interest to the public safety community; the UE is the device used by first responders to both send and receive data.

2. DISCOVERY LEARNING CENTER

The Discovery Learning Center (DLC) is the subject of investigation for the first half of our in-building study. The DLC is located on the campus of the University of Colorado at Boulder. We chose the DLC for several reasons. First, the DLC is well within the coverage area of the PSCR MN. Second, the DLC is a modern structure (built in 2002), and it is has an estimated floor space of 45,000 square feet. It contains four stories above ground and a basement that is below ground. It is a steel and concrete structure with lots of window area. The windows contain a low-emission (LE) glass material that is metal-impregnated to reduce ultraviolet solar radiation—this significantly increases shielding from radio signals outside the building. This type of glass is ubiquitous in modern building construction [5]. Finally, the DLC has a connection point to the Boulder Regional Area Network (BRAN), which provides a direct optical fiber link between the DLC and the PSCR Boulder Lab. This connection provides a dedicated and secure fiber-optic backhaul that enables small cell deployment at the DLC. This also facilitated investigations of supplementary LTE coverage techniques to fill in areas that were not adequately covered by the PSCR MN.

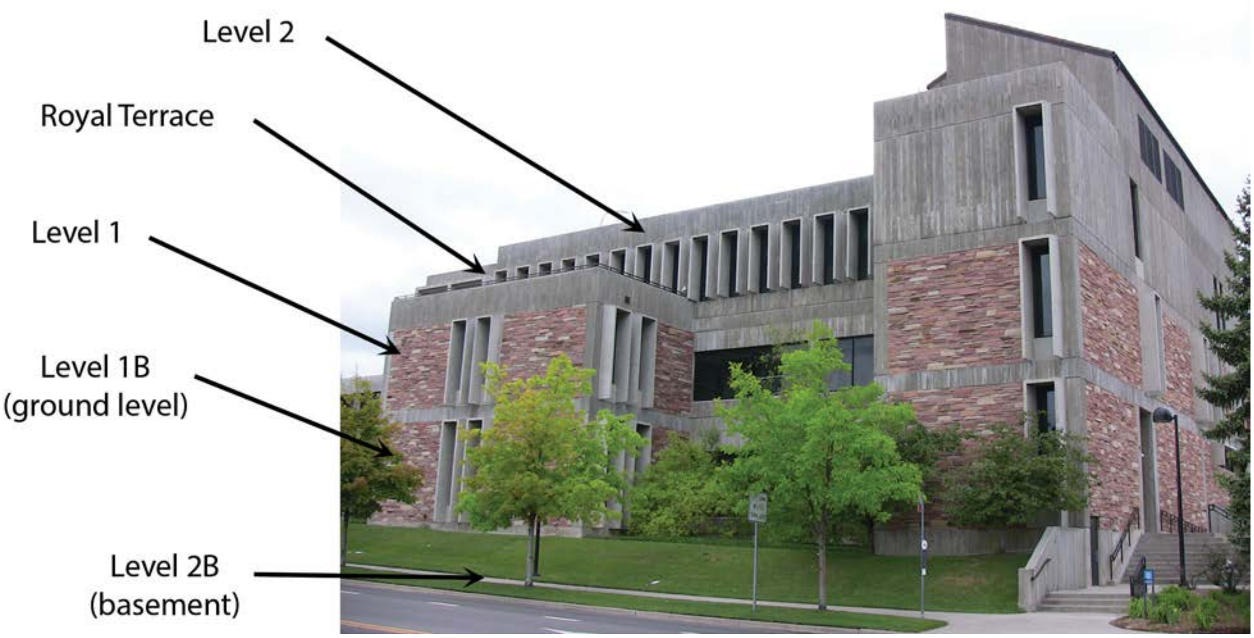

Figure 1. The Discovery Learning Center.

The four levels of the DLC are annotated in Figure 1: 1) Level 2B is a sub-basement that is located underground, 2) Level 1B is located on the ground level, 3) Level 1 is located one floor above the ground, and 4) Level 2 is the top floor that contains offices and labs. The Royal Terrace, shown in both Figures 1 and 2, is an outdoor open balcony. Figure 3 depicts the line-of-sight view from the Royal Terrace to the the evolved Node B (eNB) on Green Mountain. This eNB is part of the experimental PSCR Band 14 LTE network (see Section 4.3.1 for a description). Figure 4 shows the main entrance to the DLC which is located on the south side of the building. It consists of an open concrete framework with a glass wall behind it. The south side of the building contains a large open foyer that extends from the ground floor to the ceiling of level 2. The low-E glass on the south wall provides a significant amount of radio-frequency (RF) shielding.

Figure 2. The Royal Terrace

Figure 3. The Green Mountain eNB as viewed from the Royal Terrace.

Figure 4. The main entrance to the Discovery Learning Center. Note the open concrete framework backed by a glass wall.

2.1 Walk Test Routes

The indoor walk tests covered four floors of the DLC:

- Level 2B which is the sub-basement
- Level 1B located at ground level
- Level 1
- Level 2

In addition, we performed two outdoor walk tests:

- Royal Terrace patio on the second floor
- Around the building perimeter at ground level

All the walk tests were conducted on closed paths using pre-defined waypoints for indoor navigation. The six paths that we used are depicted in Figures 5–10. Due to accessibility considerations, the indoor walk paths were primarily located along the public corridors of the DLC. The Royal Terrace walk path, shown in Figure 9, provided a line-of-sight path to the PSCR MN (Green Mountain eNB) and served to measure signals impinging on the upper level of the DLC. The second outdoor path, shown in Figure 10, was located at ground level and was used as an additional reference to measure signals impinging on lower levels of the DLC.

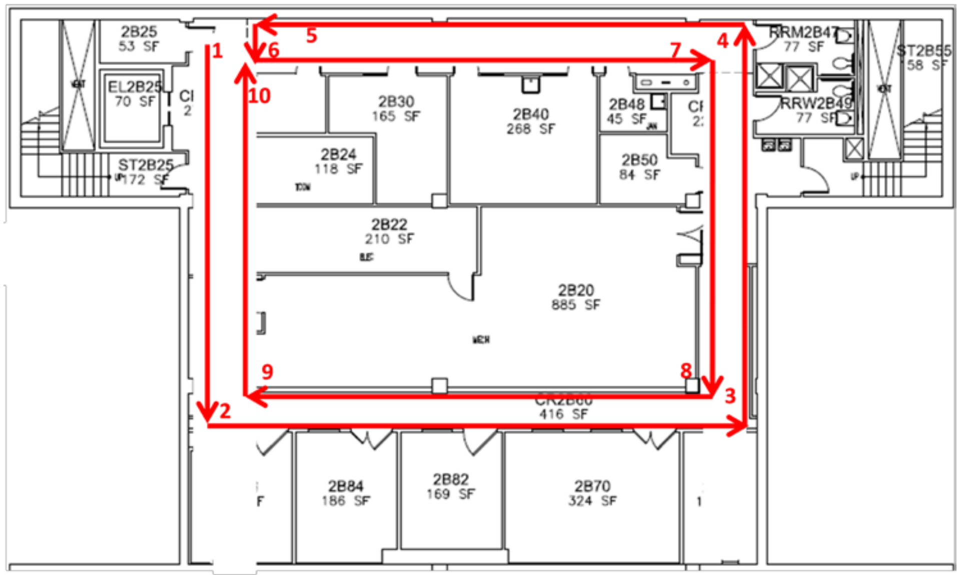

Figure 5. Walk path on level 2B (basement) of the DLC. The navigation waypoints (1–10) are numbered in increasing order from start to finish.

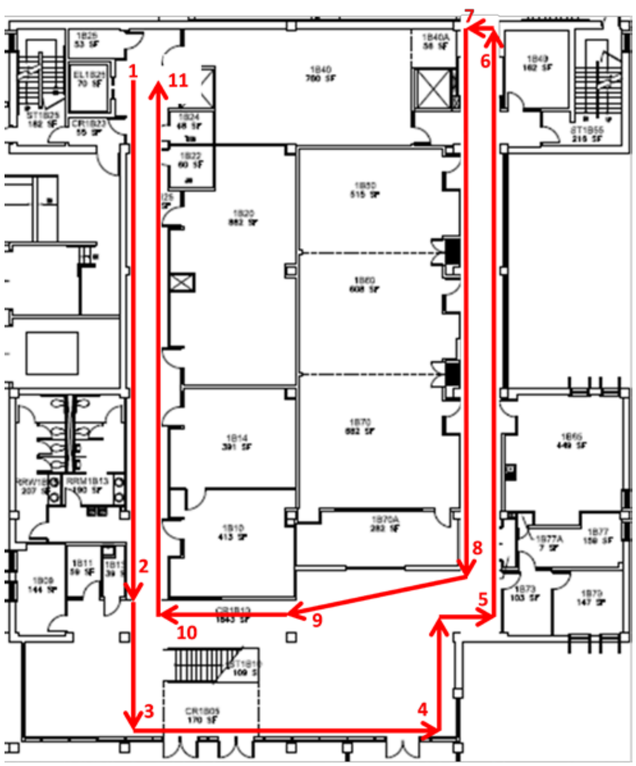

Figure 6. Walk path on level 1B (ground level) of the DLC. The navigation waypoints (1–11) are numbered in increasing order from start to finish.

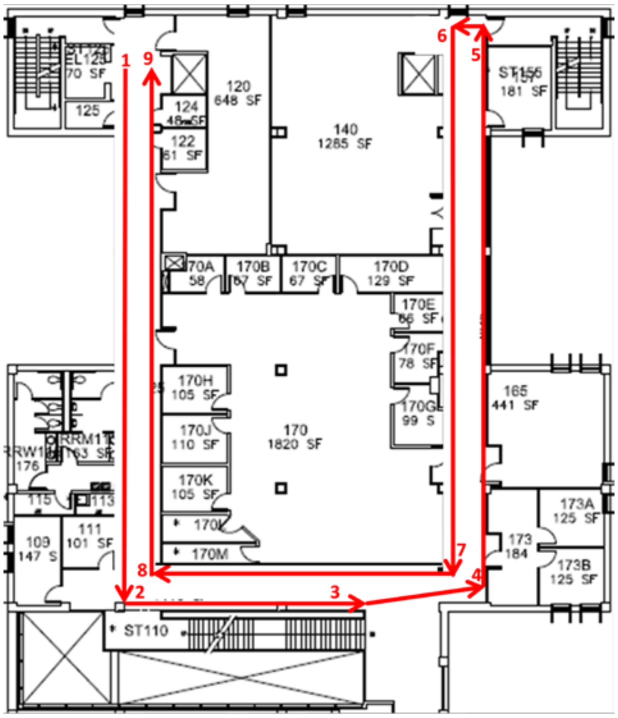

Figure 7. Walk path on level 1 of the DLC. The navigation waypoints (1–9) are numbered in increasing order from start to finish.

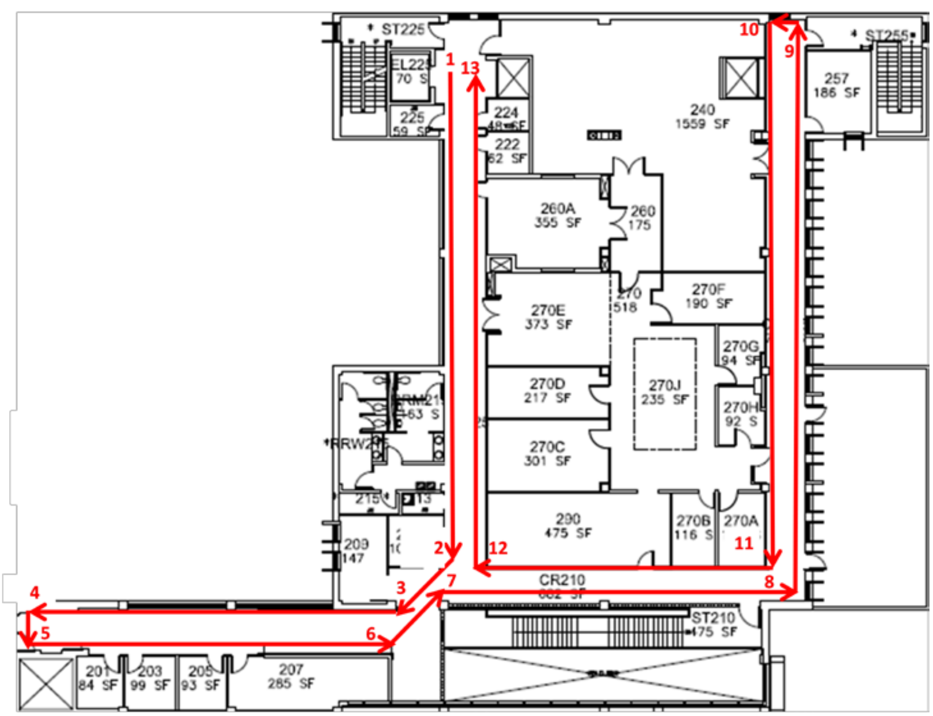

Figure 8. Walk path on level 2 of the DLC. The navigation waypoints (1–13) are numbered in increasing order from start to finish.

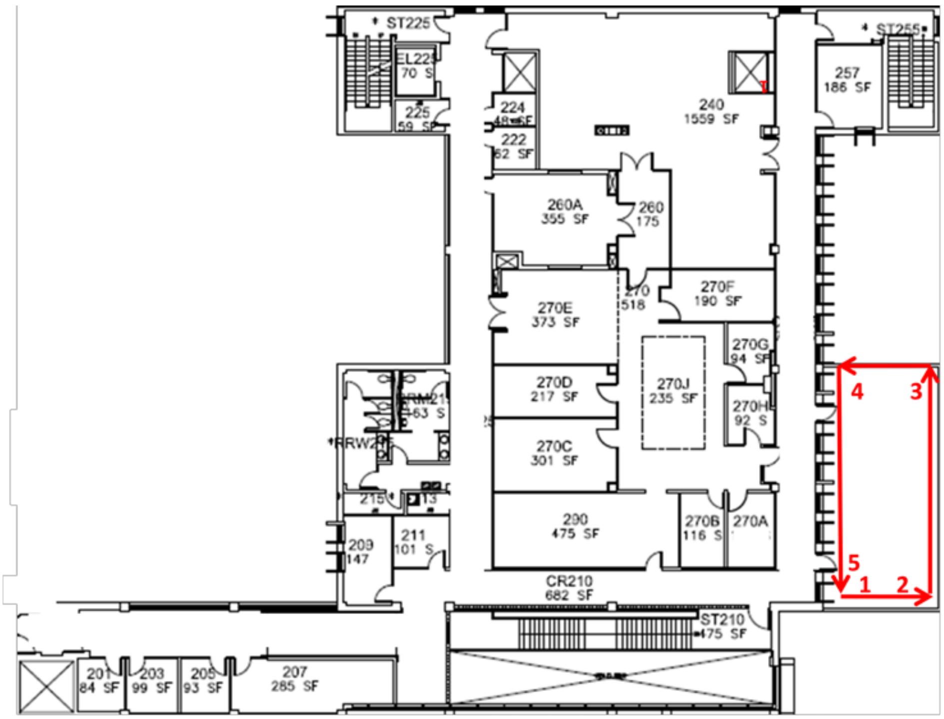

Figure 9. Walk path on the level 2 Royal Terrace of the DLC. The navigation waypoints (1–5) are numbered in increasing order from start to finish

Figure 10. Outdoor walk path around the perimeter of the DLC. The navigation waypoints (1–6) are numbered in increasing order from start to finish. The Digital Energy Laboratory, where the small cell was placed, is located on the north end (top) of the DLC and the PSCR MN illuminates the DLC from the bottom left corner of the figure.

2.2 Walk Test Measurement System

Measurements were performed using a combination of a backpack-mounted system and a tablet computer. Two independent LTE data streams were collected using a combination of a vendor-supplied LTE Modem (UE) and an LTE scanner. The data streams were, in turn, directed to a tablet computer and stored for subsequent post processing. The backpack walk testing system is shown in Figures 11–13. Figure 11 shows the functional diagram of the backpack system, and Figures 12(a) and 12(b) show the modem and scanner deployments inside the backpack. The backpack system is powered by a pair of lithium ion batteries which supply power to the UE, universal serial bus (USB) hub, and an LTE scanner. The USB hub provides the link between a tablet computer and the UE/scanner combination. The tablet computer contains drive test software that is used to configure the measurements and control data acquisition. Figure 13 shows the deployed backpack measurement system collecting both signal and LTE channel parameters.

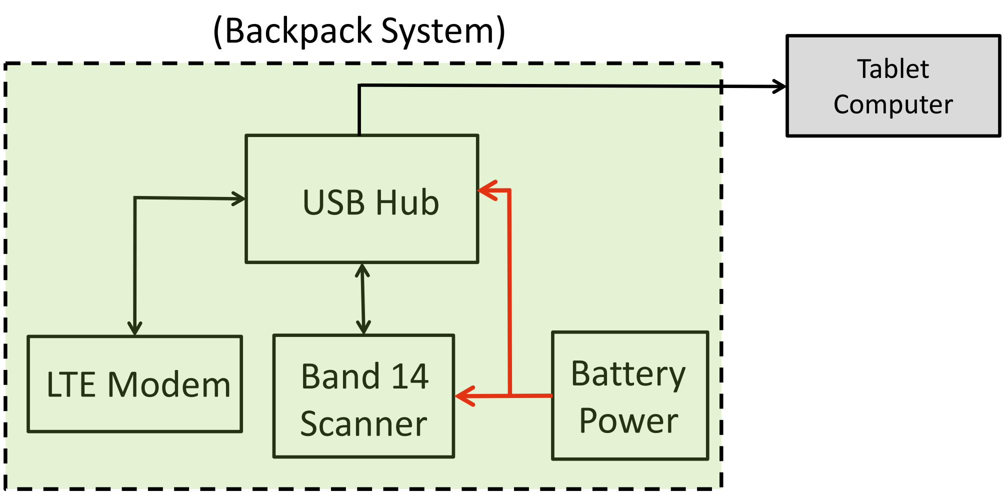

Figure 11. Functional diagram of the backpack measurement system. The USB data links are denoted by black lines and the battery power distribution by red lines.

(a) (b)

Figure 12. Backpack walk testing system with (a) LTE modem and (b) a scanner/receiver.

Figure 13. Backpack measurement system in action at the DLC, July 2013.

2.3 Measured Parameters

The backpack measurement system captures an asynchronous data stream from both the scanner and the UE and sends it to a tablet computer over a connecting USB cable. The scanner is used to capture both spectrum and LTE channel parameter information. The scanner is programmed using commercially-available drive test software to function as two distinct virtual instruments. The details of this procedure are described in the PSCR in-building test plan [6].

We configure the scanner to function both as a spectrum analyzer and an LTE channel analyzer. The spectrum analyzer is set up to perform time-averaged spectrum measurements across the frequency range of 757–769 MHz, covering the entire Band 14 downlink channel. We also added an LTE channel analyzer to the scanner and configured it to measure selected LTE parameters. The scanner is a passive, receive-only instrument, and it collects data even if there is no uplink established. It also provides additional data sets that can be compared to the UE data to check the data integrity. No scanner data is presented in this report for the sake of brevity and since the UE data is of much more interest to public safety radio-system designers.

The UE establishes a full-duplex data communications link with the PSCR LTE network and it captures a large number of RF signal, LTE, and network data parameters which are, in turn, recorded by the drive test software. Because of the large number of LTE parameters and coverage combinations, we present DLC results only for selected LTE parameters:

- Reference signal received power (RSRP)
- Carrier to interference and noise ratio (CINR)
- Physical downlink shared channel (PDSCH) data throughput rates
- Physical uplink shared channel (PUSCH) data throughput rates
- UE transmitted power

2.4 In-Building Coverage Configurations

To study LTE in-building performance at the DLC, we used the PSCR MN as our baseline and then provided supplemental coverage using a COW and a small cell. During the course of the testing, we investigated in-building LTE system performance for the following coverage configurations:

1) The PSCR Band 14 LTE macro network (baseline)
2) A COW transmitting at 8 W
3) A COW transmitting at 40 W
4) The combination of the COW transmitting at 40 W and the PSCR MN
5) A small cell with discrete antennas (SCDA) deployed on the ground floor (level 1B)
6) A small cell feeding a DAS system (SCDAS) designed by students at the University of Colorado and deployed on the ground floor of the DLC (level 1B)
7) The combination of the PSCR MN, SCDA, and a COW transmitting at 8 W
8) The combination of the PSCR MN, SCDA, and a COW transmitting at 40 W

In the case of the PSCR MN, it was not possible to establish reliable communications with the LTE modem on levels 1B and 2B due to high levels of attenuation so we do not present macro network data for these floors (item 1 above).

2.4.1 The BRAN

To establish a fast and secure backhaul network between the small cell in the DLC and the evolved packet core (EPC) back at the PSCR labs, we used the Boulder Research and Administrative Network (BRAN). The BRAN is a secure fiber optical network shared by the city of Boulder, the University of Colorado at Boulder, the National Center for Atmospheric Research (NCAR), and the Department of Commerce Boulder Laboratories. The BRAN interconnects all these organizations.

The BRAN provides a fiber optic infrastructure that gives the participating institutions efficient high speed, high-quality data communications. The fiber network is approximately 8 kilometers (11 miles) long and extends along a north-south path.

The link configuration is shown schematically in Figure 14 for an indoor small cell deployment at the DLC.

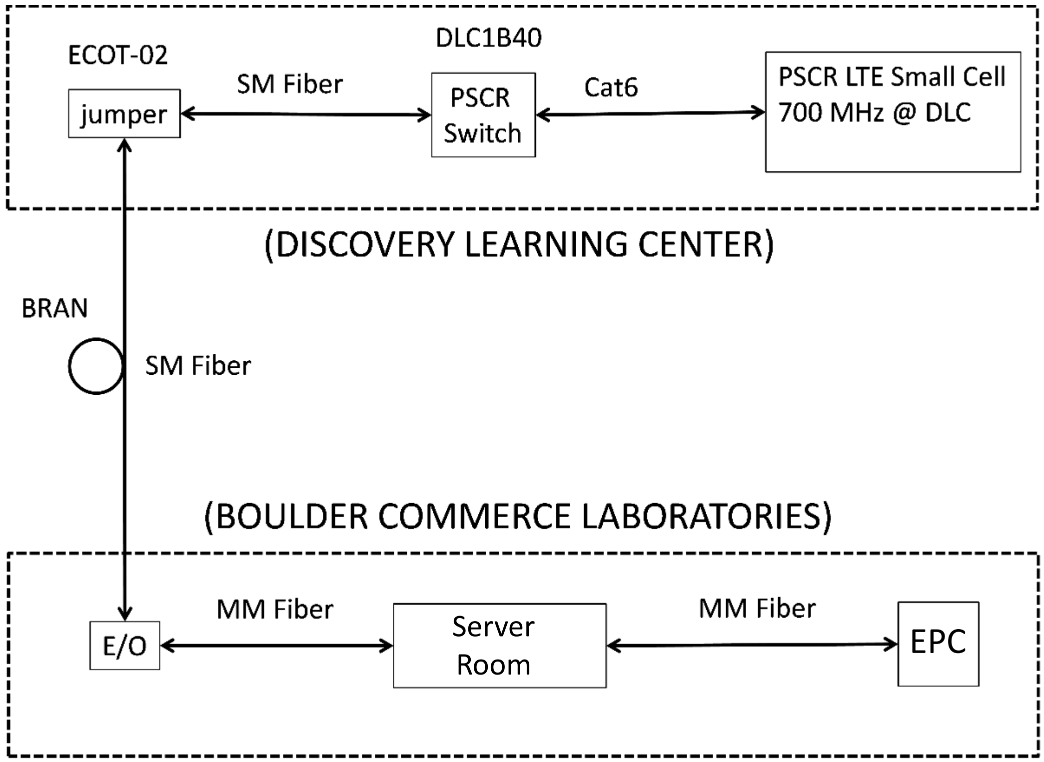

Figure 14. Schematic of the BRAN connection between the PSCR lab and the DLC.

2.4.2 The PSCR Macro Network

At the time of the DLC tests, the PSCR outdoor macro network (PSCR MN) configuration, shown in Figure 15, included two fixed sites located at Green Mountain and Table Mountain. Each site contains a number of eNBs that have been provided by different PSCR CRADA[5] partners. An eNB can be selected remotely from the PSCR radio laboratory for use in testing. Each base site has three-sector, 360 degree coverage and selectable transmission levels ranging from 10 to 80 W. The Green Mountain eNB is located 2 km from the DLC, and the Table Mountain site is 12.5 km from the DLC. Due to its proximity to the DLC, the Green Mountain eNB has the most pronounced effects at the DLC. Both the Green Mountain and Table Mountain eNBs were configured to transmit at vendor-recommended power levels of 40 W for the DLC testing. These power levels were maintained for the PSCR macro network throughout the entire program of testing.

[5] Cooperative research and development agreements (CRADA) allow private entities who intend to supply 700 MHz LTE equipment and service to public safety organizations to test interoperability of public safety communications equipment under simulated field conditions, with the participation of public safety practitioners, in the PSCR Broadband Demonstration Network. The CRADAs protect the intellectual property of vendors and manufacturers, encouraging participation in testing that simulates real multi-vendor environments in the field.

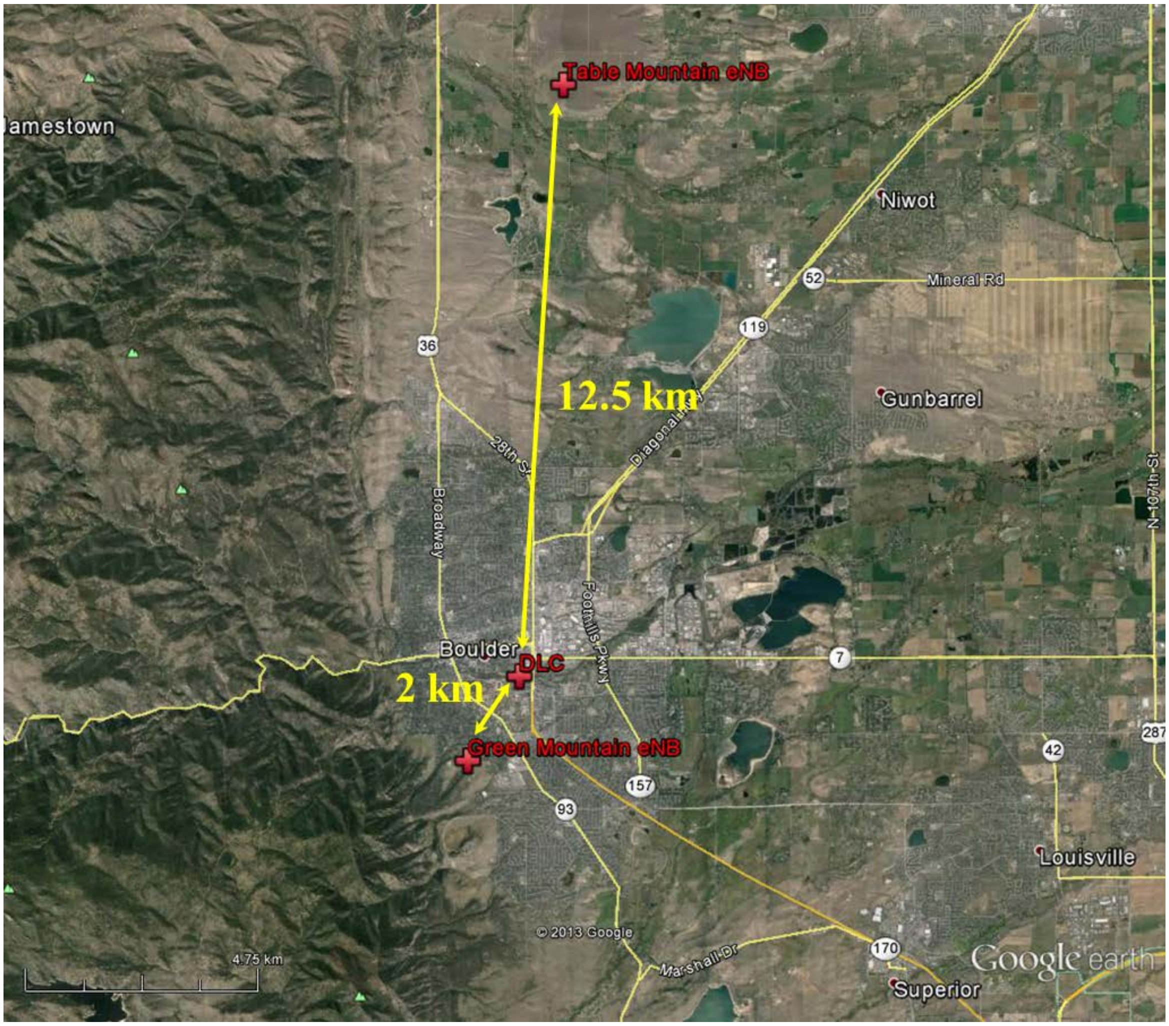

Figure 15. PSCR MN configuration relative to the Discovery Learning Center.

2.4.3 Small Cell with Discrete Antennas

The small cell configuration that was used for the tests is shown in Figure 16. The small cell has two RF antenna ports that are connected to the antennas and two Ethernet ports, one for backhaul and the other for configuring and controlling the small cell. The backhaul port was connected directly to a multiport Ethernet switch which, in turn, was connected directly into the BRAN. The control port was connected to a laptop computer with vendor-supplied software to set up, monitor, and configure the small cell. The small cell was set to an RF power level of 5 W when it was used to either provide or supplement in-building coverage.

The small cell, power supply, and multiport Ethernet switch were mounted in an equipment rack in the Digital Energy Laboratory, located in room 1B-40 on the ground floor of the DLC. The RF connections that were used are shown in Figure 16. The R0 and R1 ports of the small cell were directly connected to COTS, Band 14 capable, omnidirectional antennas as shown in Figure 17. The antenna attached to the R0 was oriented for vertical polarization with the connector port situated 0.9 m above the floor. The R1 antenna was oriented for horizontal polarization, parallel to the floor. The height of the antenna connector port above the floor was set at 0.9 m. The antennas were separated by a distance of 2 m. Figures 18 through 20 show the antenna deployment, the equipment rack, and the small cell that were used for the DLC tests. The approximate locations of the antennas that we used inside room 1B-40 are shown in Figure 21.

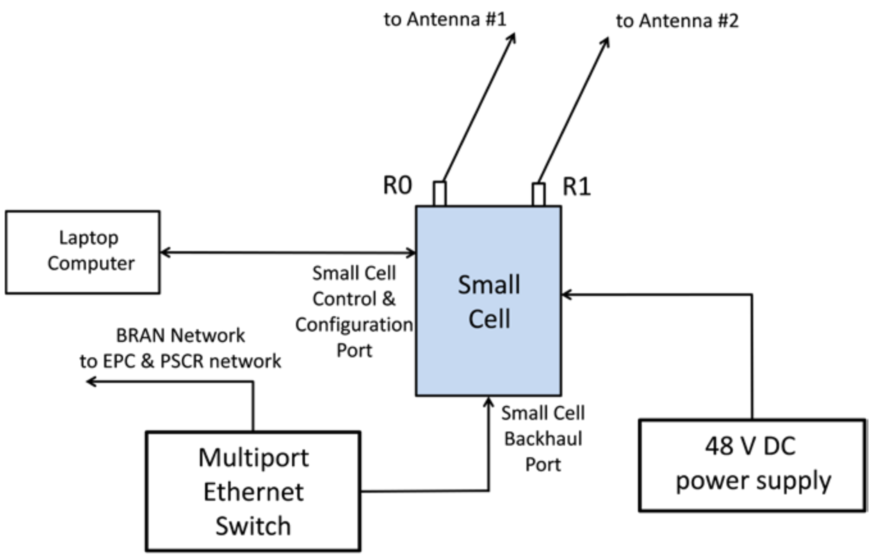

Figure 16. Single-sector small-cell configuration.

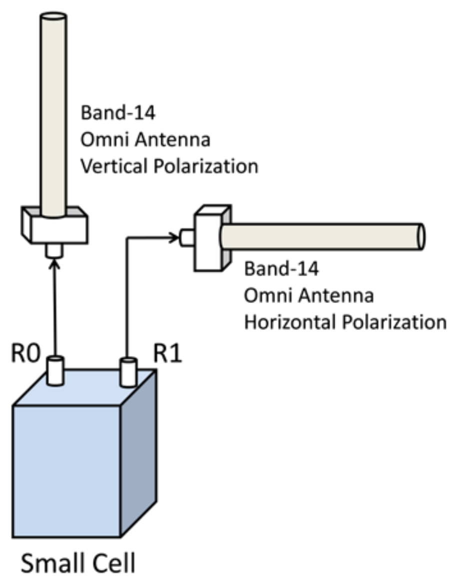

Figure 17. Antenna configuration for indoor small-cell deployment.

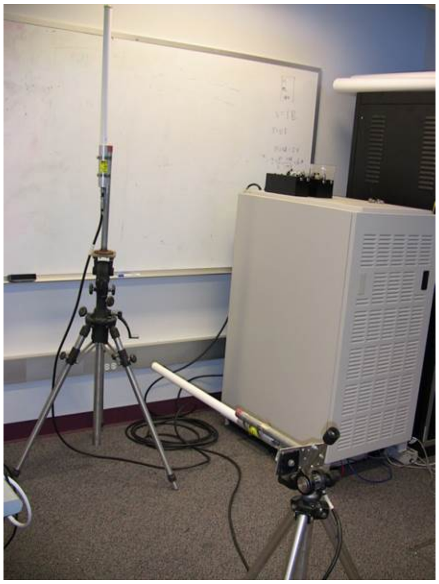

Figure 18. Antenna deployment inside the DLC.

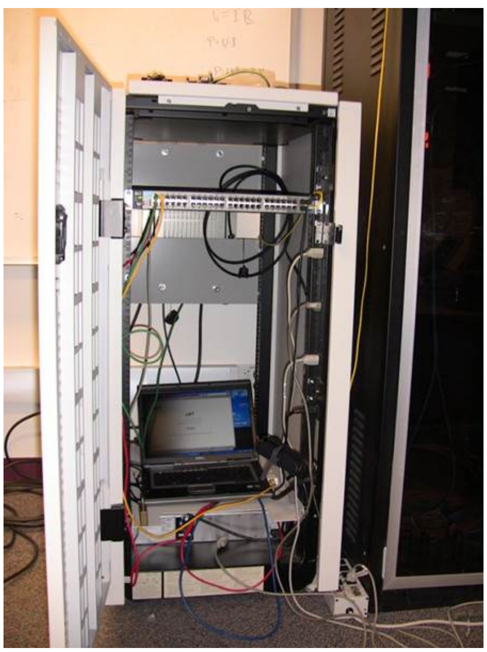

Figure 19. Equipment rack with the Ethernet switch, power supply, and a laptop to control the small cell.

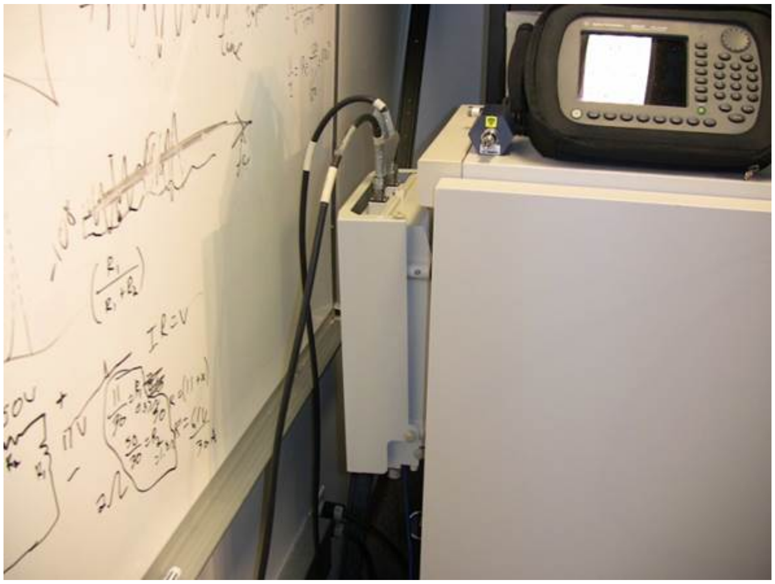

Figure 20. The small cell.

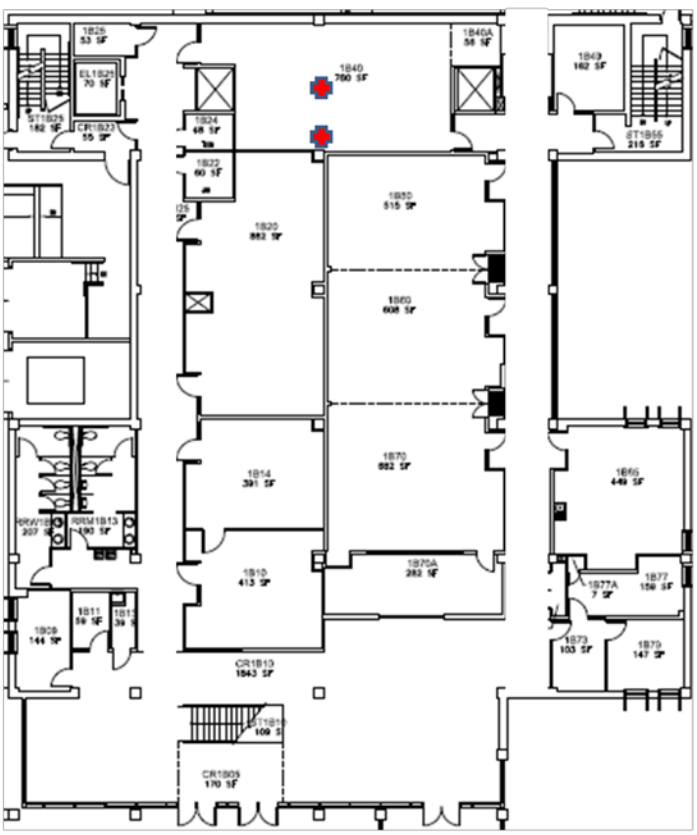

Figure 21. Approximate locations of the omni-directional antennas in room 1B-40 located on the ground floor of the DLC. The positions are marked with red crosses.

2.4.4 Small Cell with Distributed Antenna System

Dr. Ken Baker and four graduate students of the Interdisciplinary Telecommunications Program (ITP) of the University of Colorado Boulder designed and deployed a distributed antenna system (DAS) on level 1B of the DLC [7]. This system was a passive design with four ceiling-mounted antennas fed by a network of couplers and low-loss coaxial cable. A novel aspect of this design was the use of a small cell to feed the network. Typically, a DAS is fed by a macro cell [8],[9] [8], but the ITP team felt that a small cell would be far more suitable for this application due to lower costs and reduced energy requirements.

The layout of the DAS system is shown in Figure 22. Two pairs of COTS antennas were symmetrically deployed in two hallways on level 1B. The same small cell/equipment rack combination that was used to feed discrete antennas was also used to feed this DAS network. Two antennas were placed on the ceilings in each of the hallway at a separation of approximately 0.6 m as is shown in Figures 23 and 24. For each of the antenna pairs, one antenna was fed by the R0 port of the small cell and the other was fed by the R1 port in order to provide full MIMO performance. The network was fed by a network consisting of low-loss coaxial cables, directional couplers, and terminating resistors. Figures 25 and 26 show the passive components and the DAS installation, respectively. Figure 27 shows a close up view of small-cell feed for the DAS system.

The DAS feed network was designed to provide +23 dBm (200 mW) at each antenna port, which is approximately the same level of power as a Wi-Fi access point.

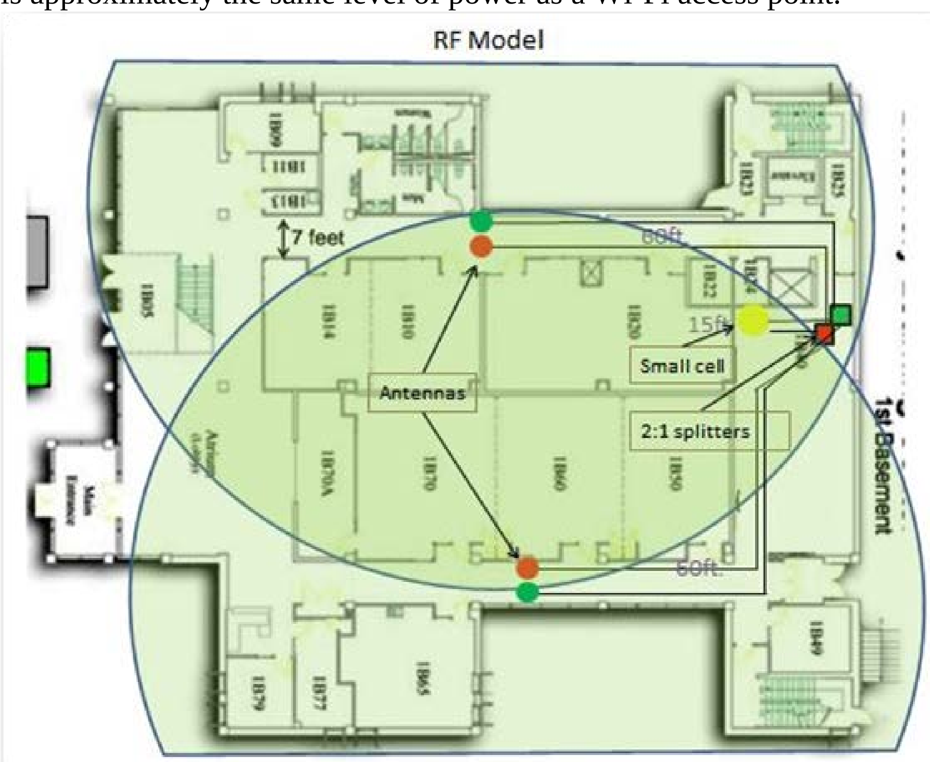

Figure 22. ITP-designed passive DAS layout on level 1B in the DLC. The direction west is at the top of the figure.

Figure 23. Antenna placement on the ceiling of the DLC.

Figure 24. Full MIMO antenna pair located on the ceiling of the DLC.

Figure 25. Passive components used in the ITP-designed passive DAS system.

Figure 26. Installation of the DAS system at the DLC.

Figure 27. Small cell feeding the DAS network (SCDAS).

2.4.5 Cell on Wheels

A cell on wheels (COW) was deployed in a parking lot approximately 73 m (240 ft) east of the DLC (Lot 336) as shown in Figure 28. The COW contains a single-sector eNB, network switching equipment, microwave backhaul, and power generation equipment. Figures 29 and 30 illustrate the COW deployment with the extended mast with on-board macro cells. The macro cell on the COW was used to feed a single-sector cellular panel antenna at heights of either 7.6 m (25 ft) or 12 m (40 ft). Figure 31 depicts the overall building illumination scenario. Backhaul was provided by a direct microwave link to the Green Mountain site. The panel antenna was bore sighted directly at geometric center of the DLC to improve in-building coverage. The transmit power levels of the macro cell were set at either 8 W or 40 W.

Figure 28. Approximate location of the PSCR COW in LOT 336 east of the DLC.

Figure 29. COW deployment in a parking lot located directly east of the DLC.

Figure 30. COW placement in the parking lot. Note the microwave backhaul dish antenna on the top of the mast.

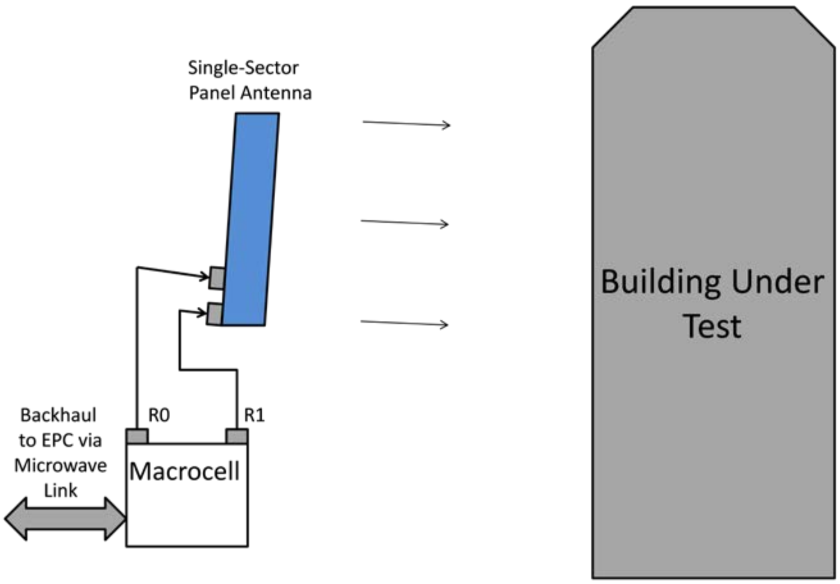

Figure 31. Building illumination scenario using the COW.

3. DLC MEASURED RESULTS

Measurements were performed for the coverage configurations described in Section 2.4. In most cases, measurements were performed over the four floors of the DLC as well as the two outside walk routes. The approach was to provide direct intercomparisons of selected LTE parameters for the various coverage configurations.

We transmitted data over the radio link between the UE in the backpack measurement system and the serving eNB. We used Netperf Version 1.0.3.22 to create UDP and TCP data transfers in both uplink and downlink directions between the UE in the backpack measurement system and the serving eNB in the PSCR laboratory, for a total of four distinct data transfer scenarios. Netperf is a graphical-user interface (GUI) controlled network bandwidth testing software that can operate in many different environments and is well suited for use on tablet computers. The Netperf configurations and implementation are fully described in [6].

Because of the large number of LTE parameters and coverage combinations, we present DLC results only for the following LTE parameters:

- Reference signal received power (RSRP)
- Carrier to interference and noise ratio (CINR)
- Physical downlink shared channel (PDSCH) data throughput rates
- Physical uplink shared channel (PUSCH) data throughput rates
- UE transmitted power

3.1 DLC Level 2B Measured Results

Level 2B of the DLC is a basement located below ground level. As a result of this location and the steel and concrete construction, the PSCR MN provides no coverage whatsoever in this part of the building. It is not possible to set up a connection with the UE in the backpack at any location on this level. We can only achieve connectivity using either the small cell or a COW parked outside the building.

Results are obtained on level 2B for the following six coverage types:

- Small cell and discrete antennas (SCDA) only with 5 W input
- COW only at 8W
- COW only at 40W
- PSCR MN + SCDA with 5 W input
- PSCR MN + SCDA with 5 W input + COW at 40 W
- PSCR MN + SCDA with 5 W input + COW at 8 W

Figures 32 through 37 depict measured reference signal received power (RSRP) results superimposed on the level 2B floor plan. Results are shown for all six coverage combinations with a TCP downlink data flow. Our measurements indicated that the RSRP levels were virtually independent of the data flow type and direction. A study of the RSRP results shows that the highest absolute signal levels occur when a SCDA is active in the coverage configuration. Our measurements also show that in the basement of the DLC the PSCR MN has virtually no effect—the small cell and the COW dominate the in-building coverage.

Figures 38–41 contain histograms of the RSRP results for the four data transfer scenarios and the five or six different coverage types tested for each scenario (we did not perform measurements for UDP data flows when we were using the SCDA as the only source of in-building coverage). Each histogram shows results for six "coverage types" (as they are called in Section 3.1). The histograms provide a count of the number of data points that fall into specified ranges of measured values. The histogram bin ranges are automatically selected by the processing software. The binning process is based on both the number of data points and range of the data. The bin ranges provide a convenient and useful display of the distribution of the measured data. A summary of basic RSRP statistics is given in Tables 1–4.

An examination of the figures and associated tables reveals several trends. First, the SCDA significantly improves the signal levels inside the DLC. Second, the addition of the COW does not significantly improve in-building coverage over that of a stand-alone SCDA. For the case of the COW providing stand-alone coverage at 8 W of power, it is surprising that we cannot achieve connectivity throughout the entire walk route. This can be seen on the left side of Figure 32 where there are missing data points. This indicates that there is no connectivity between our UE and COW over that portion of the walk route. In order to achieve connectivity over the entire walk route, we have to increase the COW transmit power to 40 W—the results of this change are shown in Figure 33.

Another interesting result is the fact that the measured RSRP results do not vary much as a function of data flow direction. This comes as no surprise, but it does indicate that the measurement system is working properly and that the measurements have good repeatability.

Figures 42 through 45, along with Tables 5–8, show results for carrier to interference-plus-noise (CINR). This LTE parameter is a signal-to-noise ratio, where the signal component is the LTE channel power, and the noise component consists of both an environmental component and interference generated by neighbor cells (when multiple eNB elements are used). In general, LTE system performance improves with increasing CINR.

When the small-cell support using the SCDA system is present, the CINR values range from roughly 12 dB to 30 dB, which indicates good system performance. When the COW is used at either 8 W or 40 W, the spread of CINR values covers the entire performance range from poor to good (−26 dB to 26 dB). This is due to the wide variation in path loss which occurs over the walk route. The path loss is at a minimum on the east side of the building, facing the COW, and increases rapidly as the walk test position moves away from that position. It is also interesting to see that the shapes of the resulting distributions change as a function of the data flow direction. This indicates that the noise levels also change with the direction of data flow.

The data rate results for both PDSCH and PUSCH are depicted in Figures 46–49 and Tables 9−12 for both the TCP and UDP data flows. The poorest performance occurs when coverage is provided by the COW alone. In this case, we see the highest data rates on the east side of the DLC, where the COW is located, due to lower path losses. The data rates rapidly decrease on the west side of the DLC because the additional building structural materials located between the COW and the UE result in higher RF path losses. This variability in path losses results in a large spread in data rates that vary from a minimum of 0 kb/s to a maximum of nearly 30 Mb/s. The addition of the small cell with discrete antennas to the coverage provides a significant performance improvement due primarily to reduced serving cell path losses. Very low data rates are no longer observed and maximum data rates approaching 50 Mb/s are seen for a downlink data flow and 20 Mb/s for an uplink data flow.

Figures 50–53 and Tables 13–16 depict the transmit power levels of the UE for both TCP and UDP. Several trends are apparent. First, the UE has to transmit at higher levels when the COW is the only source of coverage. This is, once again, due to high path losses that occur in the basement of the DLC. In fact, the highest levels of UE transmit power—above +20 dBm—occur for this coverage type. The addition of the SCDA to the coverage reduces the transmit power levels. This effect is more pronounced in the downlink direction. This is because the UE transmits a much heavier data payload for an uplink data flow, which, in turn, dictates increased transmit power levels for efficient data transmission.

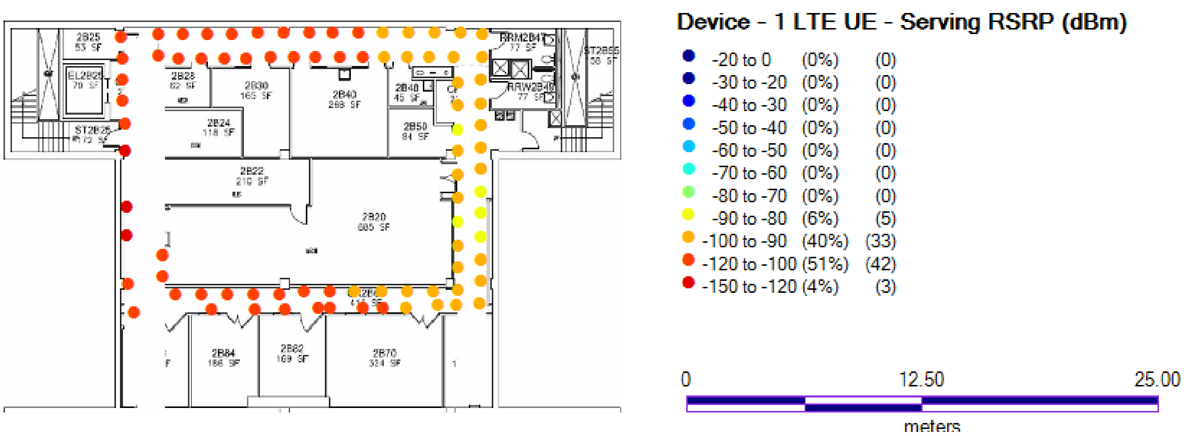

Figure 32. Level 2B reference signal received power (RSRP) for a TCP downlink data flow with the COW at 8 W. Note the lack of connectivity over some portions of the walk route.

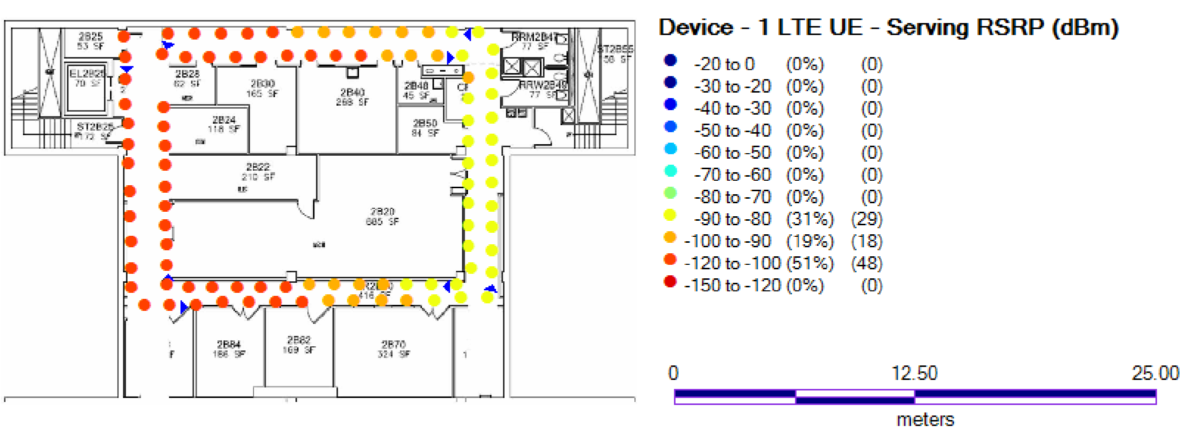

Figure 33. Level 2B reference signal received power (RSRP) for a TCP downlink data flow with the COW at 40 W.

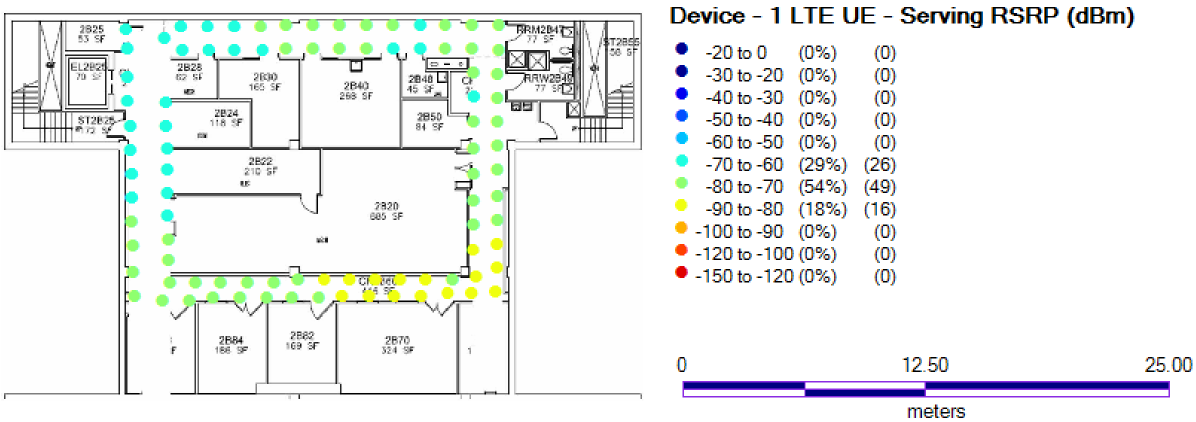

Figure 34. Level 2B reference signal received power (RSRP) for a TCP downlink data flow with the small cell at 5 W.

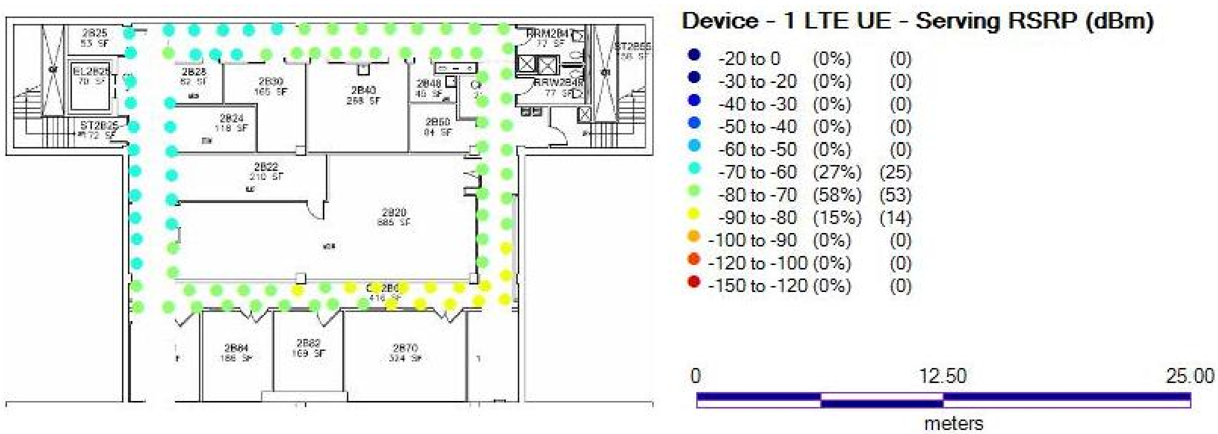

Figure 35. Level 2B reference signal received power (RSRP) for a TCP downlink data flow with the small cell at 5 W and the PSCR MN.

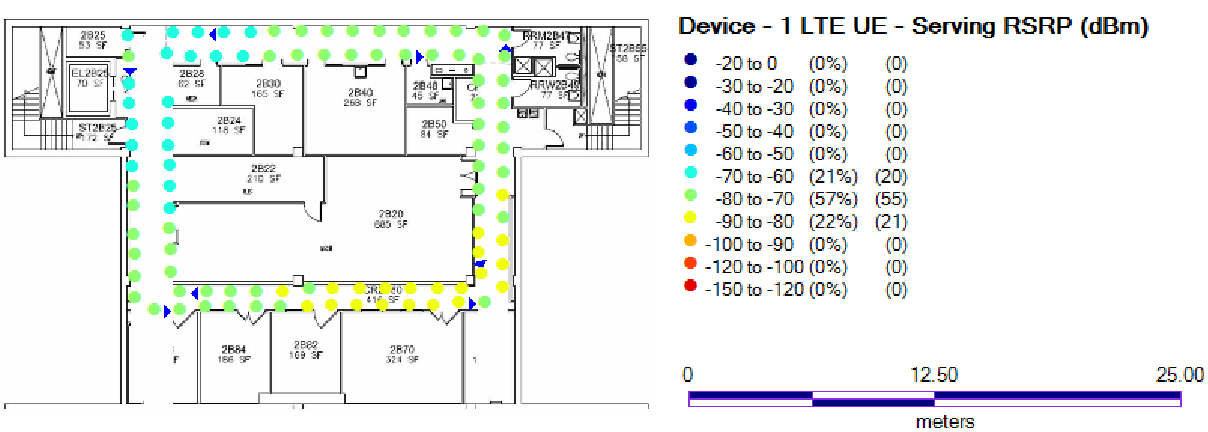

Figure 36 Level 2B reference signal received power (RSRP) for a TCP downlink data flow with the small cell at 5 W, COW at 8 W, and the PSCR MN.

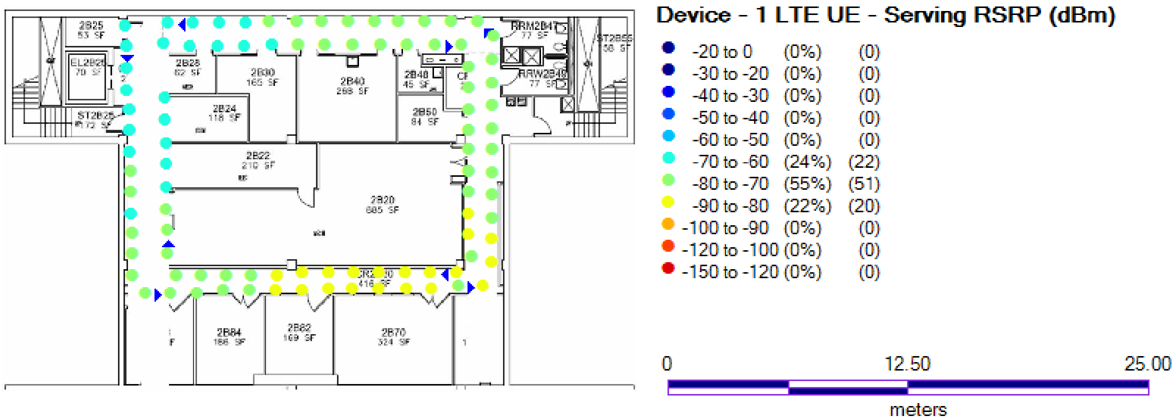

Figure 37 Level 2B reference signal received power (RSRP) for a TCP downlink data flow with the small cell at 5 W, the COW at 40 W, and the PSCR MN.

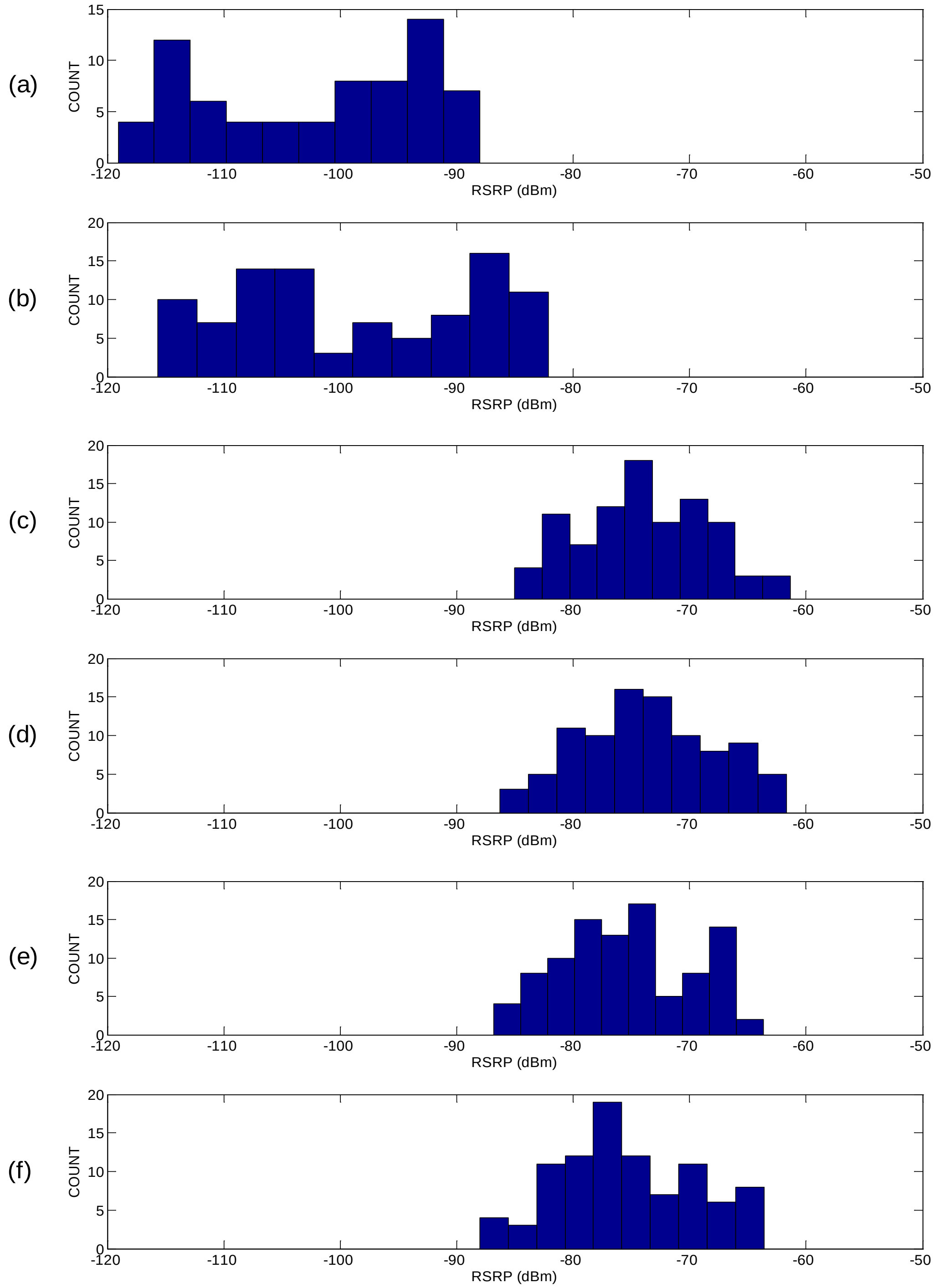

Figure 38. Level 2B histograms of RSRP for different coverage combinations with a TCP downlink data flow. (a) COW at 8 W (b) COW at 40 W, (c) small cell at 5 W with discrete antennas, (d) small cell at 5 W with discrete antennas and PSCR MN, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

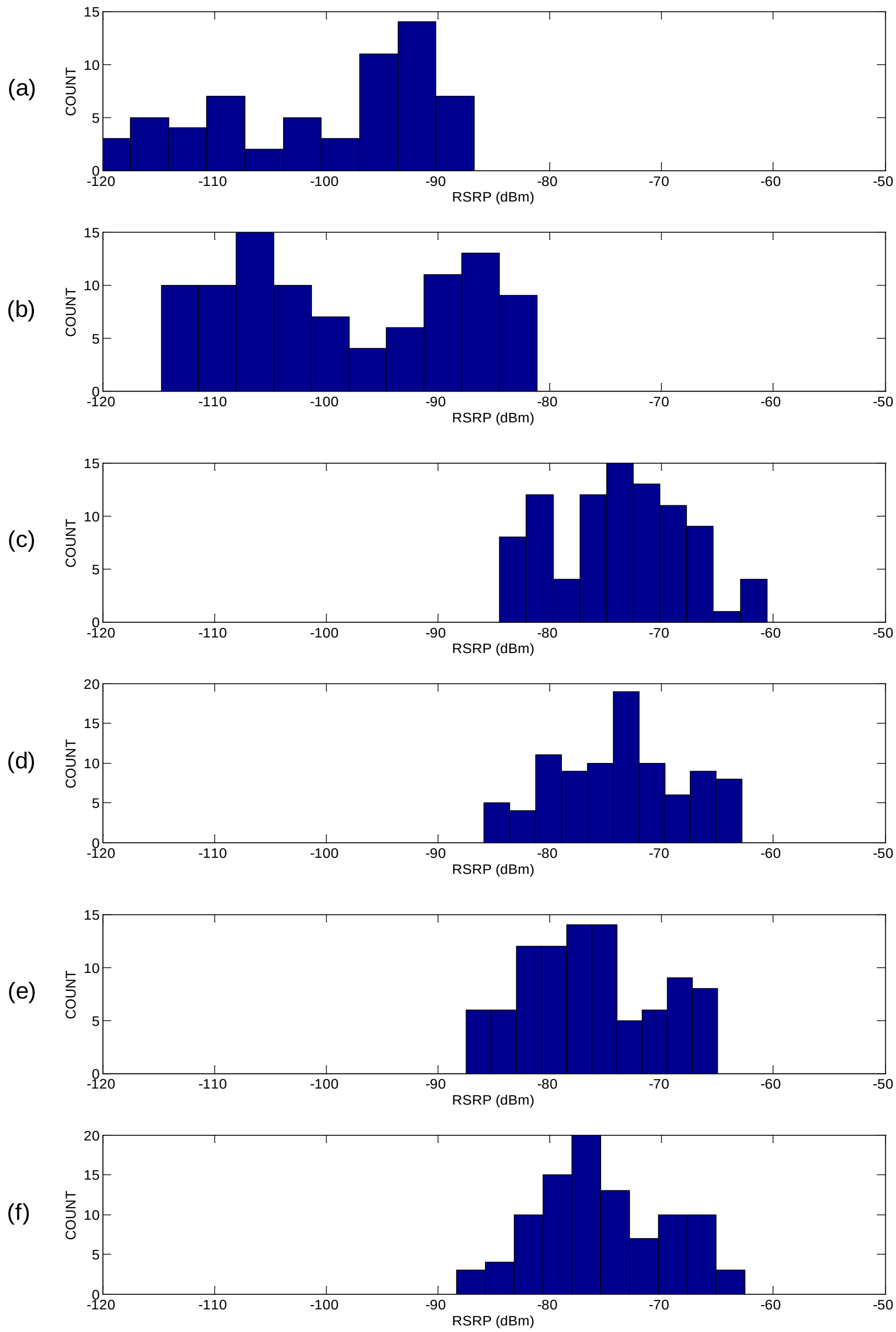

Figure 39. Level 2B RSRP histograms for different coverage combinations with a TCP uplink data flow. (a) COW at 8 W, (b) COW at 40 W, (c) small cell at 5 W with discrete antennas, (d) small cell at 5 W with discrete antennas and PSCR MN, (e) small cell at 5 W with discrete antennas PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

Table 1. Level 2B RSRP statistics for a TCP downlink data flow.

Coverage Combination	**Mean RSRP (dBm)**	**Median RSRP (dBm)**	**Standard Deviation (dBm)**	**Min RSRP (dBm)**	**Max RSRP (dBm)**
COW 8 W	-102.1	-99.3	9.5	-119.1	-88.0
COW 40 W	-98.7	-100.9	10.2	-115.7	-82.1
SCDA 5 W	-73.8	-73.7	5.4	-85.0	-61.4
SCDA 5 W+ PSCR MN	-73.5	-73.8	5.8	-86.3	-61.7
SCDA 5 W + COW 8 W+ PSCR MN	-75.4	-75.5	5.7	-86.8	-63.6
SCDA 5 W + COW 40 W + PSCR MN	-75.3	-76.0	5.9	-88.0	-63.6

Table 2. Level 2B RSRP statistics for a TCP uplink data flow.

Coverage Combination	**Mean RSRP (dBm)**	**Median RSRP (dBm)**	**Standard Deviation (dBm)**	**Min RSRP (dBm)**	**Max RSRP (dBm)**
COW 8 W	-100.4	-95.9	9.7	-120.9	-86.8
COW 40 W	-98.4	-99.6	10.1	-114.8	-81.2
SCDA 5 W	-73.8	-74.0	5.7	-85.5	-60.6
SCDA 5 W+ PSCR MN	-73.6	-73.8	5.8	-85.9	-62.8
SCDA 5 W + COW 8 W+ PSCR MN	-76.4	-76.9	5.9	-87.5	-65.0
SCDA 5 W + COW 40 W + PSCR MN	-75.3	-75.8	5.8	-88.3	-62.6

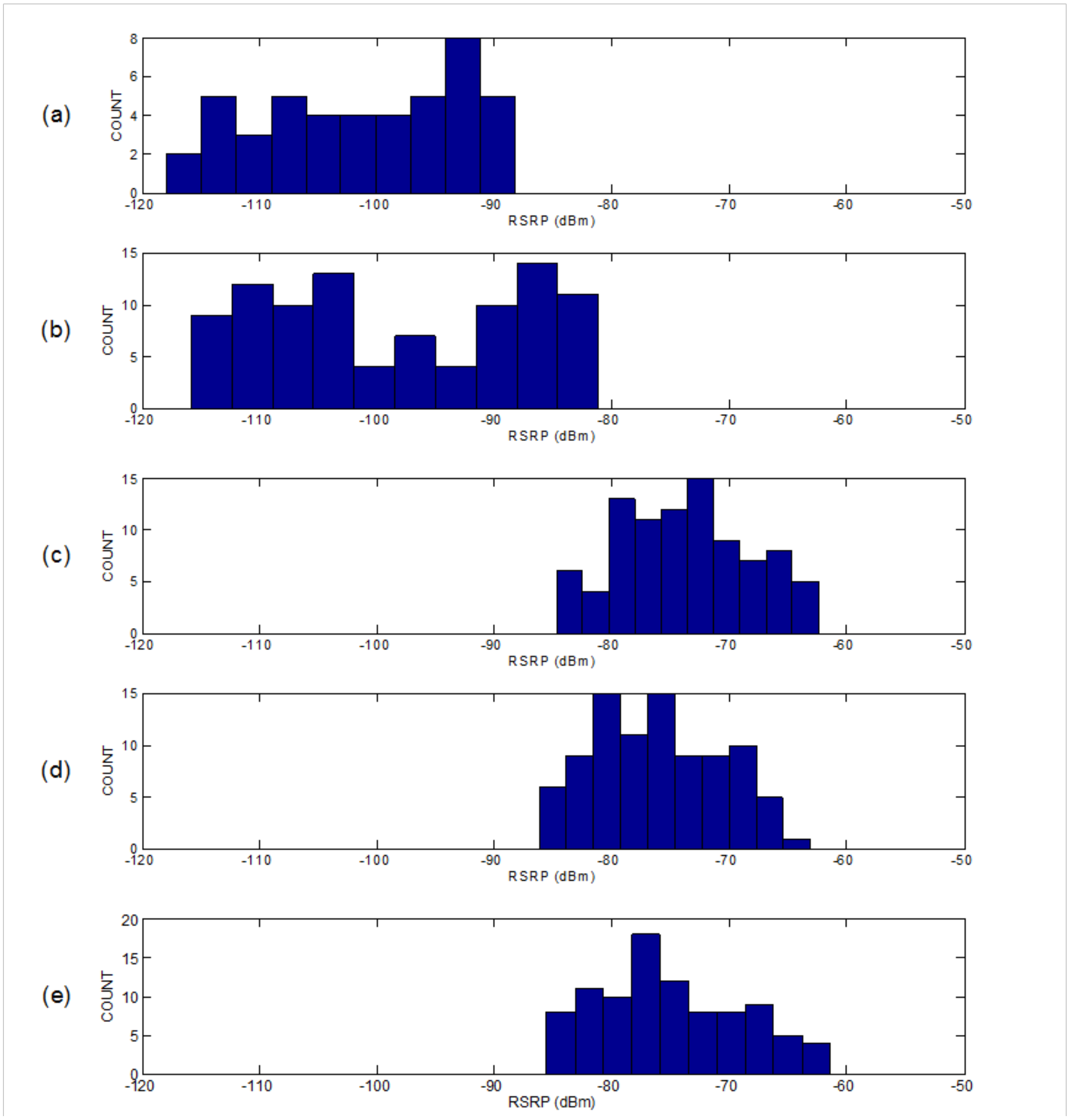

Figure 40. Level 2B histograms of RSRP for different coverage combinations with UDP downlink data flow. (a) COW at 8 W, (b) COW at 40 W, (c) small cell at 5 W with discrete antennas and PSCR MN, (d) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

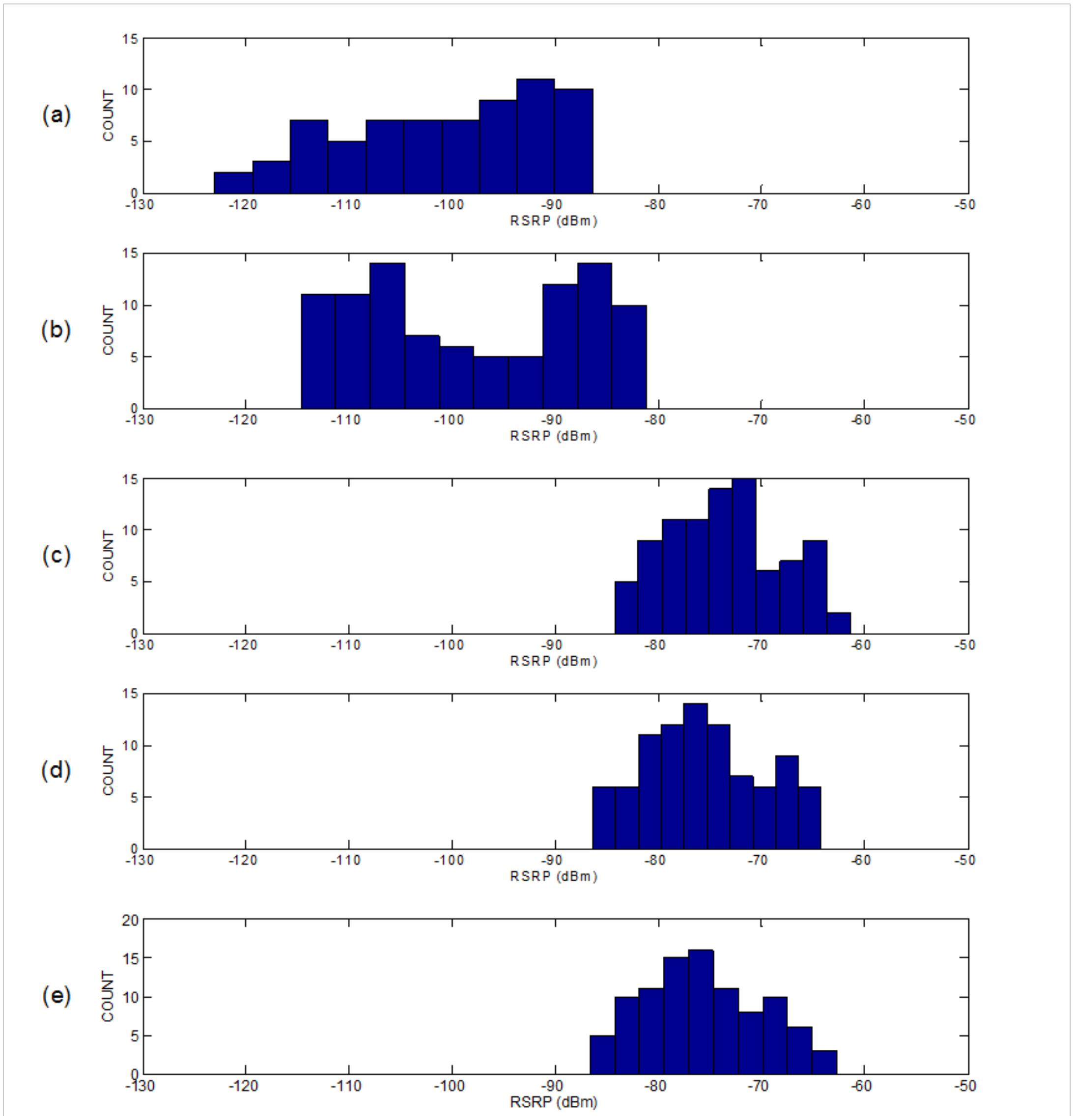

Figure 41. Level 2B histograms of RSRP for different coverage combinations with a UDP uplink protocol. (a) COW at 8 W, (b) COW at 40 W, (c) small cell at 5 W with discrete antennas and PSCR MN, (d) small cell at 5 W with discrete antennas and PSCR MN, and COW at 8 W, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

Table 3. Level 2B RSRP statistics for a UDP downlink data flow.

Coverage Combination	**Mean RSRP (dBm)**	**Median RSRP (dBm)**	**Standard Deviation (dBm)**	**Min RSRP (dBm)**	**Max RSRP (dBm)**
COW 8 W	-101.4	-100.2	8.6	-117.9	-88.2
COW 40 W	-98.5	-101.0	10.6	-115.8	-81.2
SCDA 5 W+ PSCR MN	-73.7	-73.6	5.6	-84.7	-62.4
SCDA 5 W + COW 8 W+ PSCR MN	-76.1	-76.0	5.5	-86.2	-63.1
SCDA 5 W + COW 40 W + PSCR MN	-75.0	-75.0	6.1	-85.5	-61.4

Table 4. Level 2B RSRP statistics for a UDP uplink data flow.

Coverage Combination	**Mean RSRP (dBm)**	**Median RSRP (dBm)**	**Standard Deviation (dBm)**	**Min RSRP (dBm)**	**Max RSRP (dBm)**
COW 8 W	-101.0	-99.6	9.6	-123.0	-86.4
COW 40 W	-98.0	-99.5	10.4	-114.6	-81.2
SCDA 5 W+ PSCR MN	-73.5	-73.8	5.5	-84.2	-61.4
SCDA 5 W + COW 8 W+ PSCR MN	-75.4	-75.7	5.8	-86.3	-64.2
SCDA 5 W + COW 40 W + PSCR MN	-75.6	76.0	5.8	-86.6	-62.7

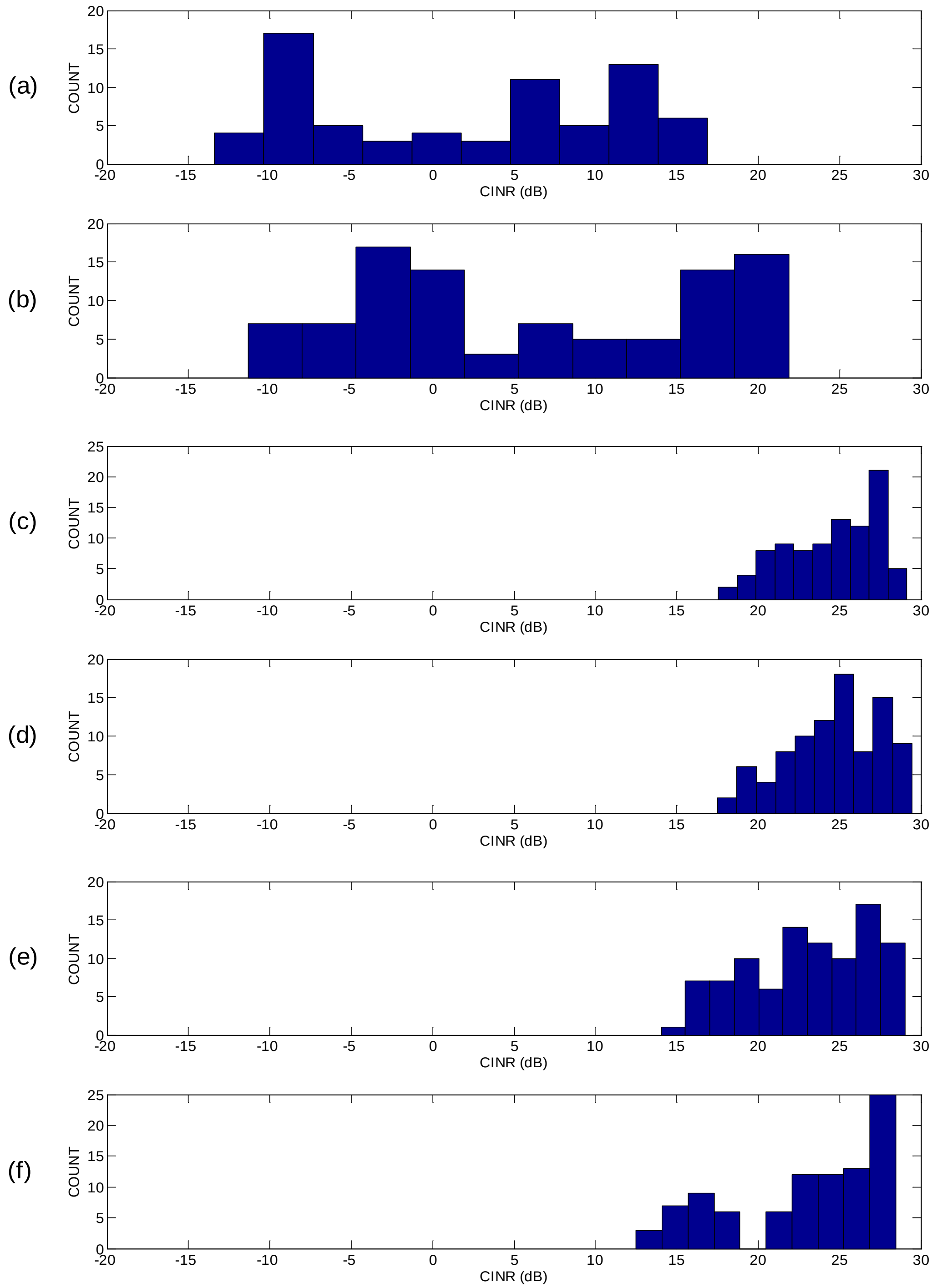

Figure 42. Level 2B histograms of CINR for different coverage combinations with a TCP downlink data flow. (a) COW at 8 W (b) COW at 40 W, (c) small cell at 5 W with discrete antennas, (d) small cell at 5 W with discrete antennas and PSCR MN, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

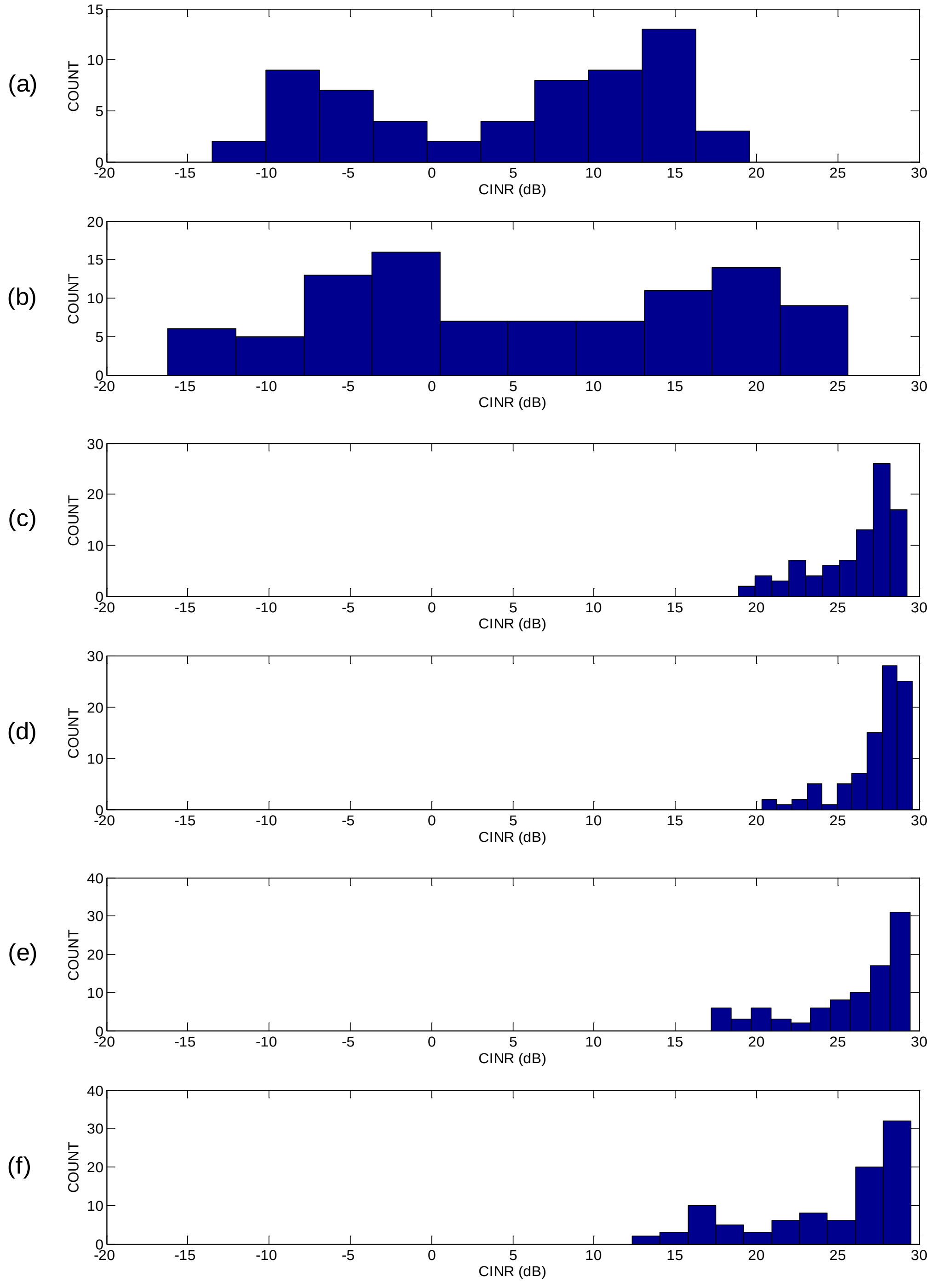

Figure 43. Level 2B histograms of CINR for different coverage combinations with a TCP uplink data flow. (a) COW at 8 W (b) COW at 40 W, (c) small cell at 5 W with discrete antennas, (d) small cell at 5 W with discrete antennas and PSCR MN, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

Table 5. Level 2B CINR statistics for a TCP downlink data flow.

Coverage Combination	**Mean CINR (dBm)**	**Median CINR (dBm)**	**Standard Deviation (dBm)**	**Min CINR (dBm)**	**Max CINR (dBm)**
COW 8 W	2.0	3.8	9.3	-13.4	16.9
COW 40 W	6.3	3.8	10.3	-11.3	21.9
SCDA 5 W	24.5	25.1	2.8	17.6	29.1
SCDA 5 W+ PSCR MN	24.7	25.2	2.9	17.5	29.5
SCDA 5 W + COW 8 W+ PSCR MN	23.1	23.3	3.8	14.0	29.0
SCDA 5 W + COW 40 W + PSCR MN	22.9	24.2	4.7	12.5	28.5

Table 6. Level 2B CINR statistics for a TCP uplink data flow.

Coverage Combination	**Mean CINR (dB)**	**Median CINR (dB)**	**Standard Deviation (dB)**	**Min CINR (dB)**	**Max CINR (dB)**
COW 8 W	4.7	8.1	9.5	-13.5	19.6
COW 40 W	6.0	4.7	11.7	-16.2	25.7
SCDA 5 W	26.1	27.1	2.7	18.9	29.3
SCDA 5 W+ PSCR MN	27.4	28.1	2.1	20.3	29.6
SCDA 5 W + COW 8 W+ PSCR MN	25.8	27.2	3.6	17.2	29.5
SCDA 5 W + COW 40 W + PSCR MN	24.4	26.8	4.9	12.4	29.5

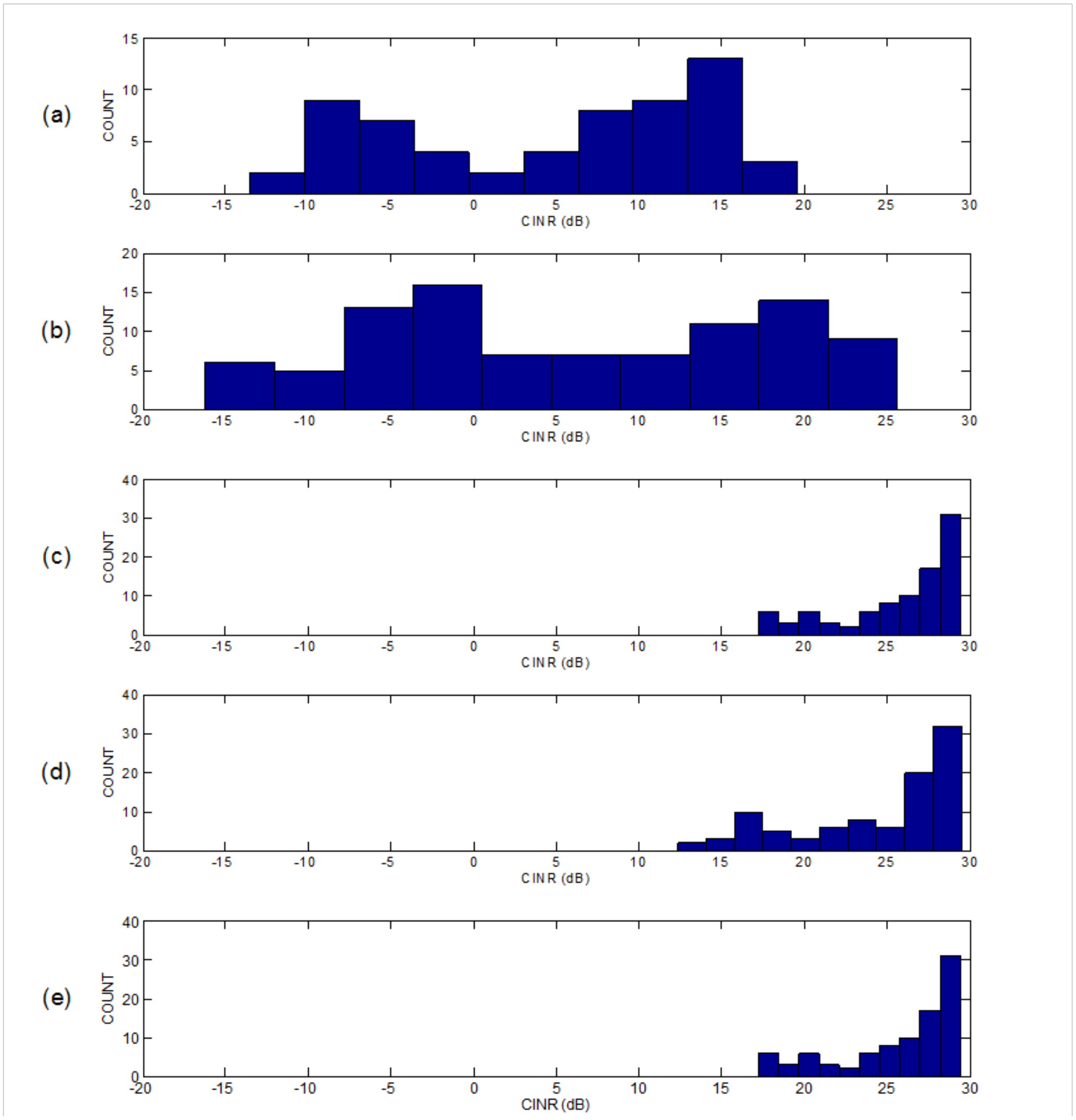

Figure 44. Level 2B histograms of CINR for different coverage combinations with a UDP downlink data flow. (a) COW at 8 W, (b) COW at 40 W, (c) small cell at 5 W with discrete antennas and PSCR MN, (d) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

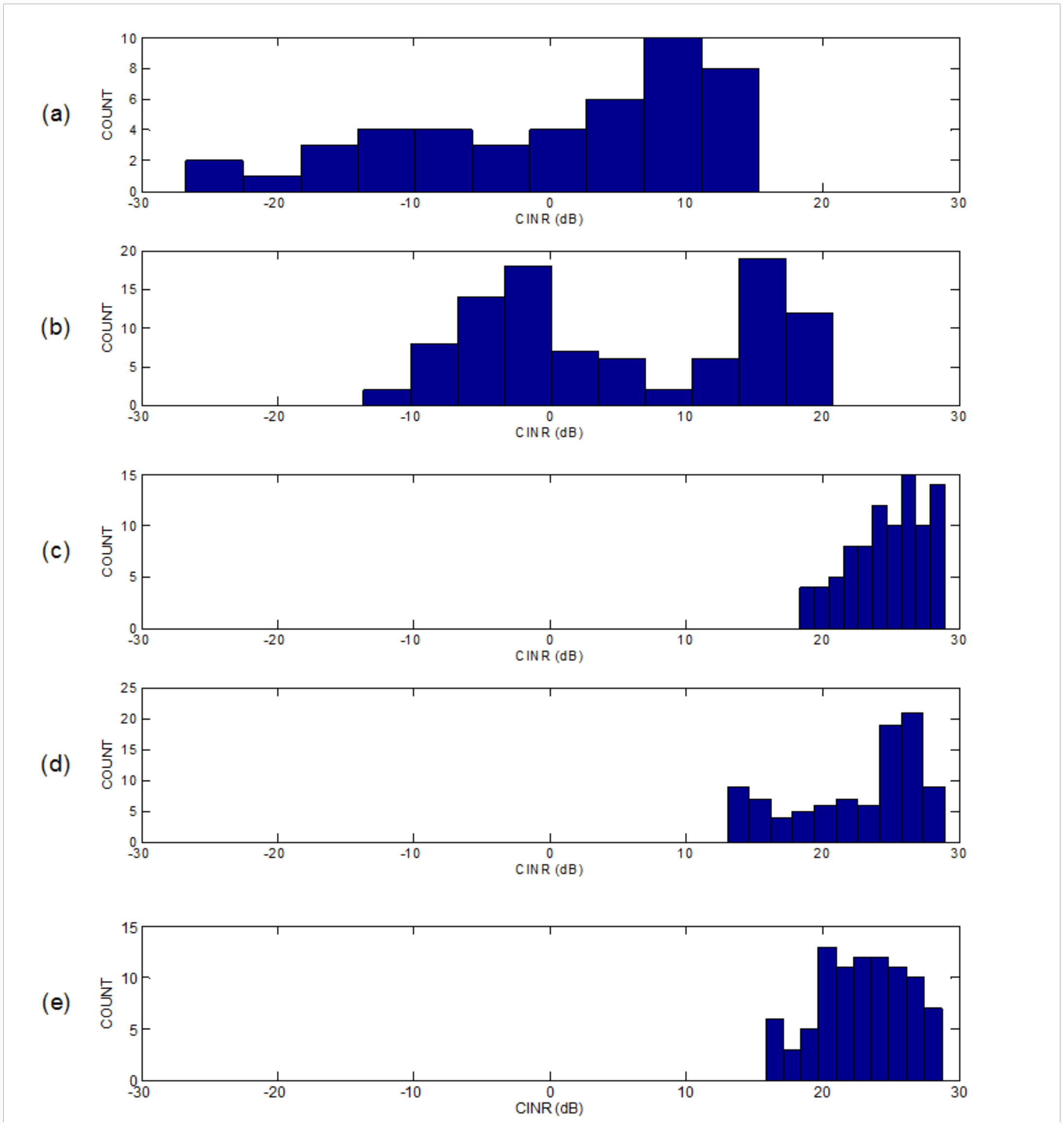

Figure 45. Level 2B histograms of CINR for different coverage combinations with a UDP uplink data flow. (a) COW at 8 W, (b) COW at 40 W, (c) small cell at 5 W with discrete antennas and PSCR MN, (d) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

Table 7. Level 2B CINR statistics for a UDP downlink data flow.

Coverage Combination	Mean CINR (dB)	Median CINR (dB)	Standard Deviation (dB)	Min CINR (dB)	Max CINR (dB)
COW 8 W	4.7	8.2	9.5	-13.5	19.6
COW 40 W	6.0	4.7	11.7	-16.2	25.7
SCDA 5 W+ PSCR MN	25.8	27.2	3.6	17.2	29.5
SCDA 5 W + COW 8 W+ PSCR MN	25.8	27.2	3.6	17.2	29.5
SCDA 5 W + COW 40 W + PSCR MN	24.4	26.8	4.9	12.4	29.5

Table 8. Level 2B CINR statistics for a UDP uplink data flow.

Coverage Combination	Mean CINR (dB)	Median CINR (dB)	Standard Deviation (dB)	Min CINR (dB)	Max CINR (dB)
COW 8 W	0.5	4.0	11.3	-26.7	15.3
COW 40 W	4.9	1.8	10.1	-13.7	20.8
SCDA 5 W+ PSCR MN	24.8	25.2	2.8	18.3	29.0
SCDA 5 W + COW 8 W+ PSCR MN	22.9	23.3	3.3	15.8	28.8
SCDA 5 W + COW 40 W + PSCR MN	22.6	24.5	4.8	13.3	29.0

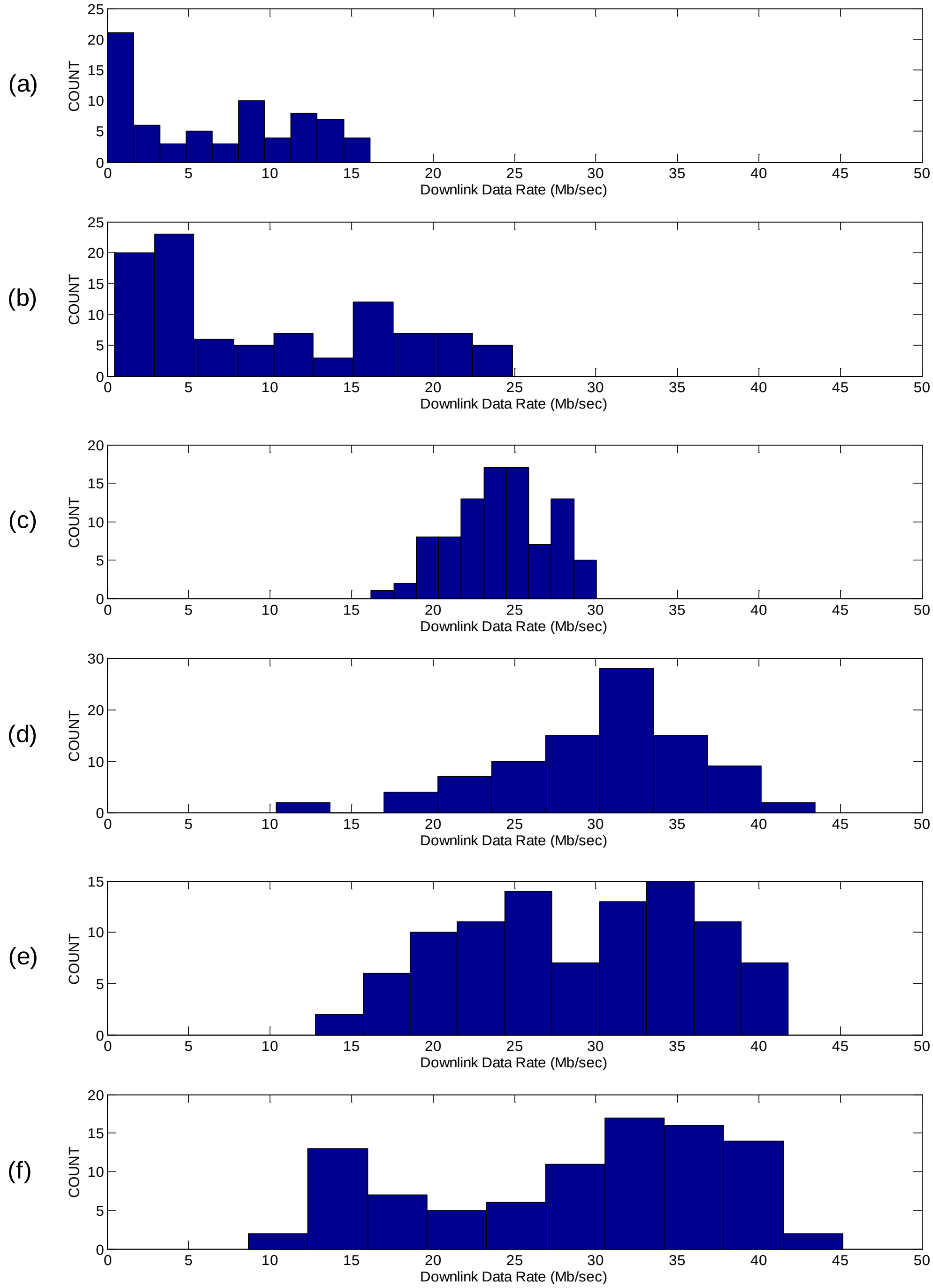

Figure 46. Level 2B histograms of PDSCH for different coverage combinations with a TCP downlink data flow. (a) COW at 8 W (b) COW at 40 W, (c) small cell at 5 W with discrete antennas, (d) small cell at 5 W with discrete antennas and PSCR MN, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

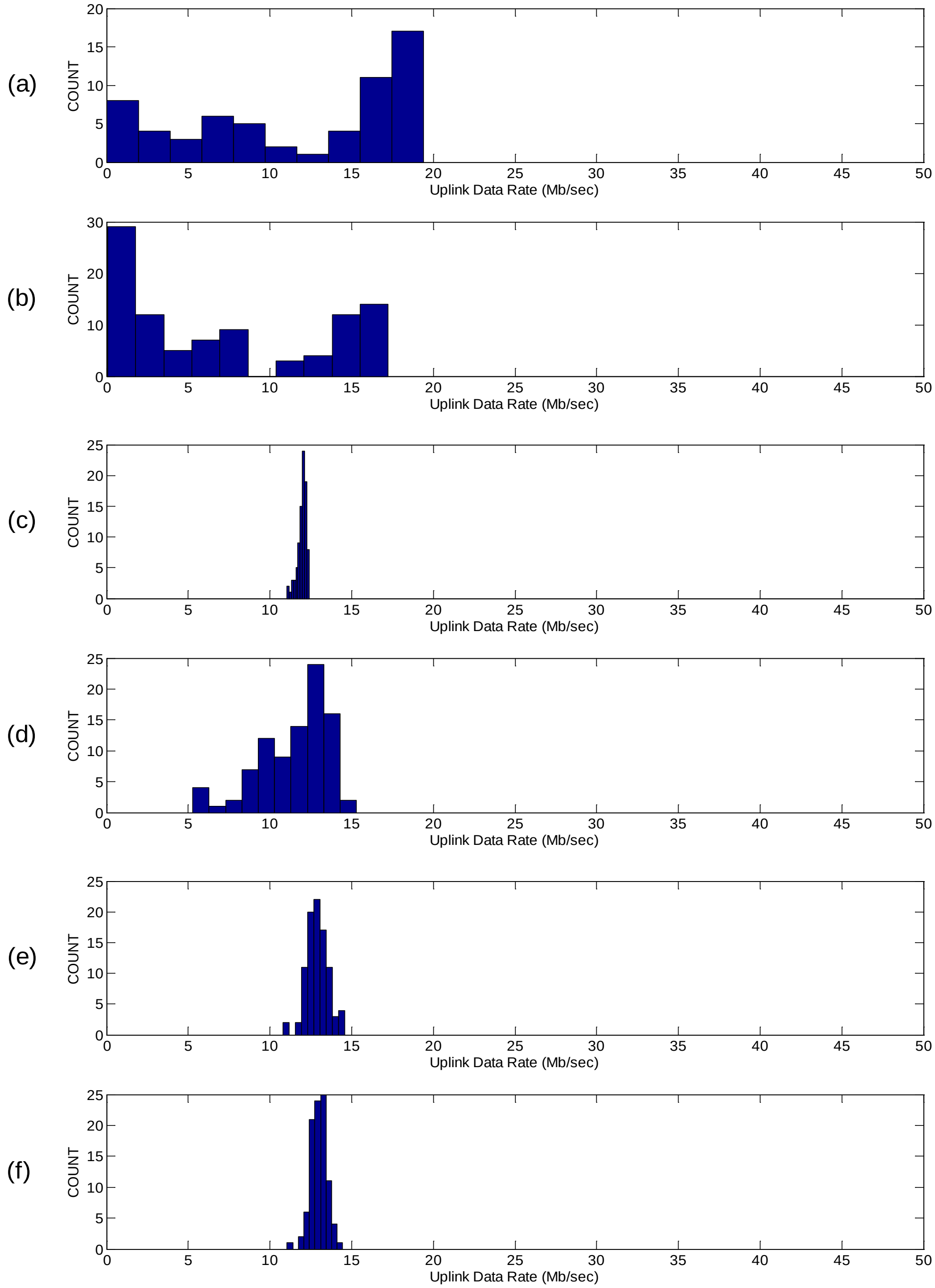

Figure 47. . Level 2B histograms of PDSCH for different coverage combinations with a TCP uplink data flow. (a) COW at 8 W (b) COW at 40 W, (c) small cell at 5 W with discrete antennas, (d) small cell at 5 W with discrete antennas and PSCR MN, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

Table 9. Level 2B PDSCH statistics for a TCP downlink data flow.

Coverage Combination	Mean PDSCH (Mb/s)	Median PDSCH (Mb/s)	Standard Deviation (Mb/s)	Min PDSCH (Mb/s)	Max PDSCH (Mb/s)
COW 8 W	6.7	7.5	5.2	0.0	16.1
COW 40 W	9.5	6.5	7.6	0.4	24.9
SCDA 5 W	24.1	24.4	3.0	16.2	30.0
SCDA 5 W+ PSCR MN	30.2	31.1	6.0	10.4	43.5
SCDA 5 W + COW 8 W+ PSCR MN	28.7	29.6	7.2	12.8	41.8
SCDA 5 W + COW 40 W + PSCR MN	28.7	31.0	9.2	8.7	45.1

Table 10. Level 2B PUSCH statistics for a TCP uplink data flow.

Coverage Combination	Mean PDSCH (Mb/s)	Median PDSCH (Mb/s)	Standard Deviation (Mb/s)	Min PDSCH (Mb/s)	Max PDSCH (Mb/s)
COW 8 W	11.6	14.9	6.7	0.0	19.4
COW 40 W	7.2	5.7	6.2	0.1	17.3
SCDA 5 W	12.0	12.0	0.3	11.0	12.4
SCDA 5 W+ PSCR MN	11.5	12.2	2.1	5.3	15.3
SCDA 5 W + COW 8 W+ PSCR MN	12.9	12.9	0.7	10.8	14.6
SCDA 5 W + COW 40 W + PSCR MN	13.0	13.0	0.5	11.1	14.5

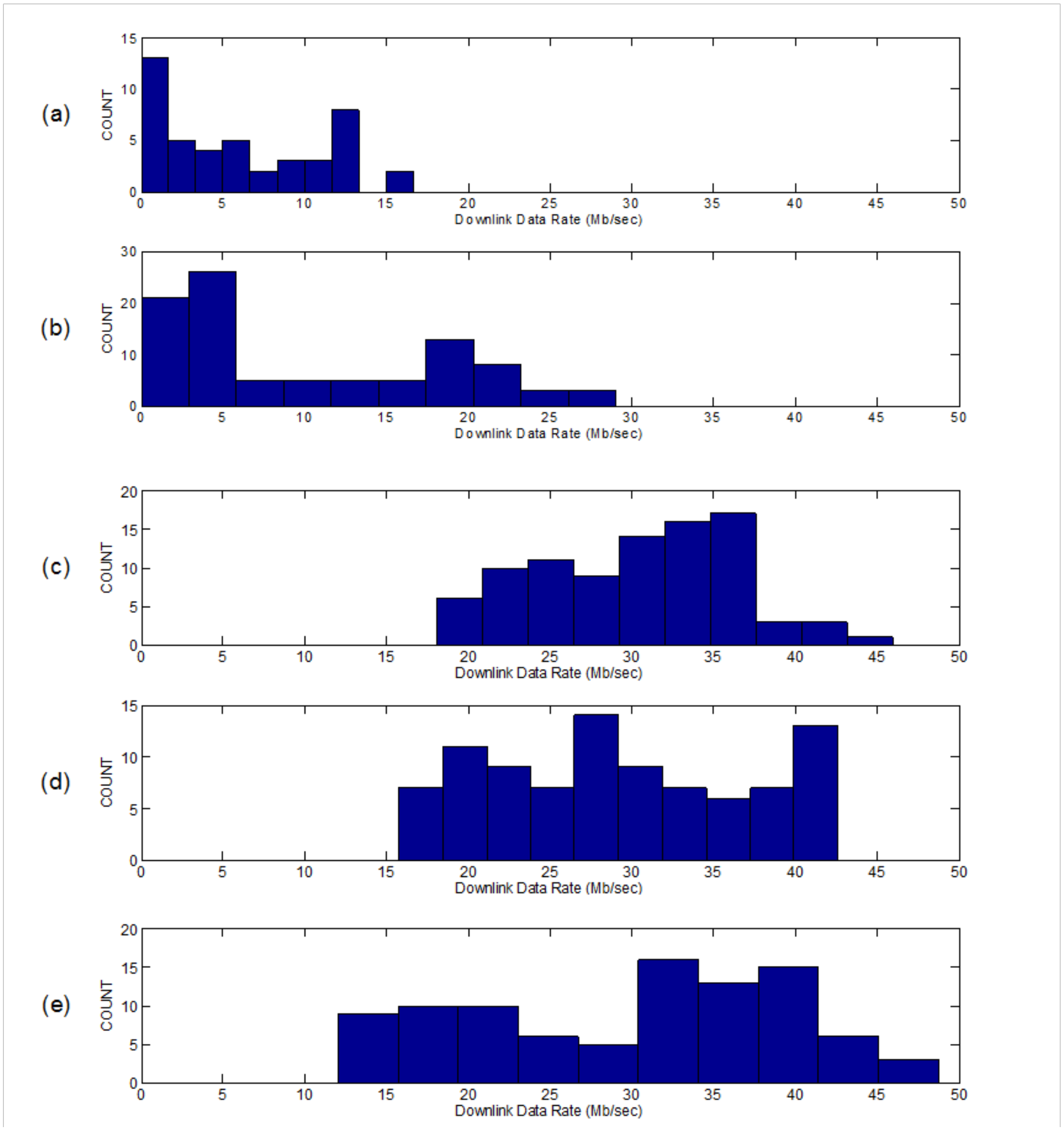

Figure 48. Level 2B histograms of PDSCH for different coverage combinations with a UDP downlink data flow. (a) COW at 8 W, (b) COW at 40 W, (c) small cell at 5 W with discrete antennas and PSCR MN, (d) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

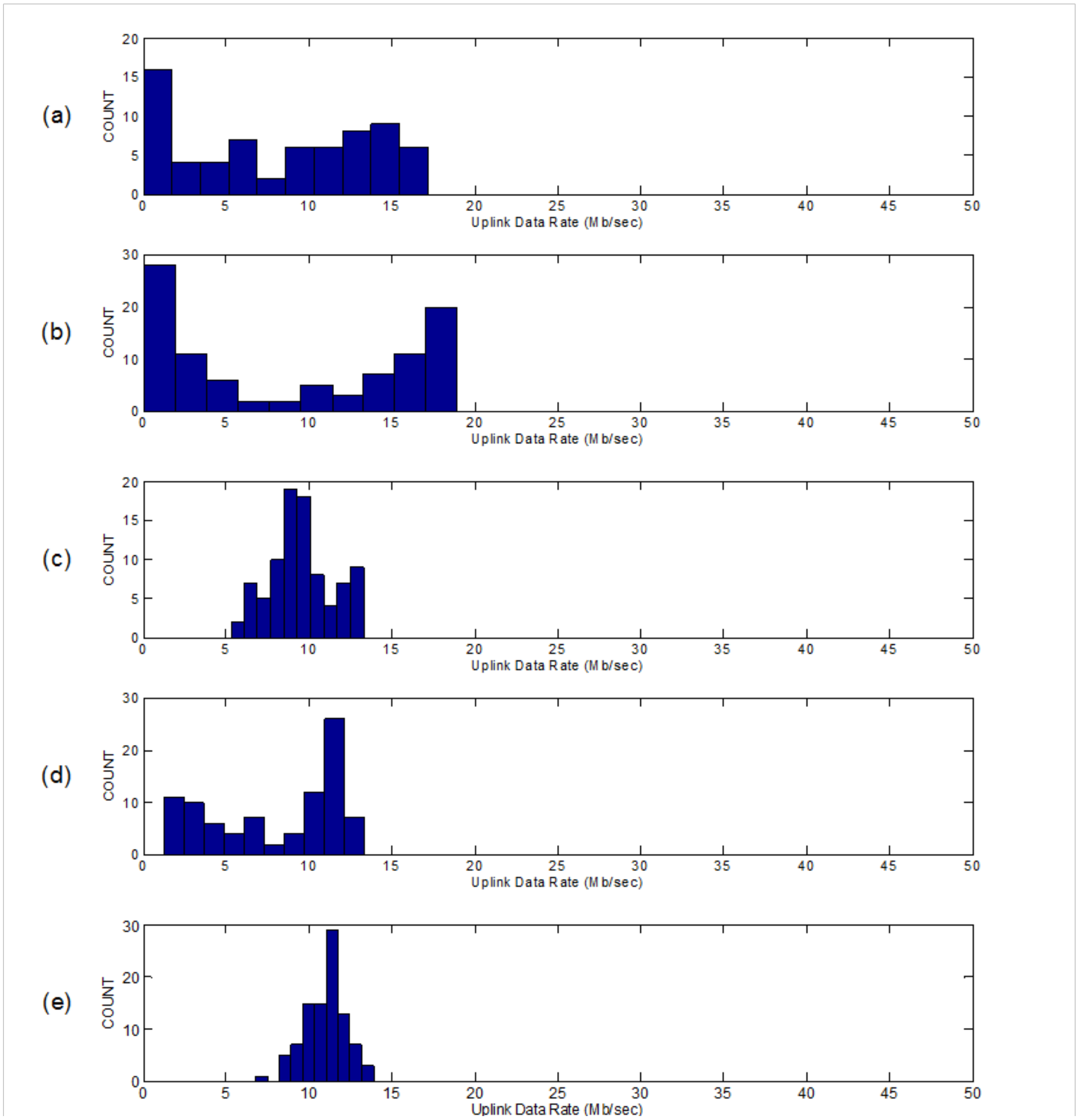

Figure 49. Level 2B histograms of PUSCH for different coverage combinations with a UDP uplink data flow. (a) COW at 8 W, (b) COW at 40 W, (c) small cell at 5 W with discrete antennas and PSCR MN, (d) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

Table 11. Level 2B PDSCH statistics for a UDP downlink data flow.

Coverage Combination	**Mean PDSCH (Mb/s)**	**Median PDSCH (Mb/s)**	**Standard Deviation (Mb/s)**	**Min PDSCH (Mb/s)**	**Max PDSCH (Mb/s)**
COW 8 W	6.2	5.2	4.9	0.0	16.6
COW 40 W	10.1	6.1	8.4	0.0	29.0
SCDA 5 W+ PSCR MN	30.5	31.4	6.2	18.1	46.0
SCDA 5 W + COW 8 W+ PSCR MN	29.2	28.8	8.0	15.8	42.6
SCDA 5 W + COW 40 W + PSCR MN	29.9	31.2	9.6	12.0	48.8

Table 12. Level 2B PUSCH statistics for a UDP uplink data flow.

Coverage Combination	**Mean PUSCH (Mb/s)**	**Median PUSCH (Mb/s)**	**Standard Deviation (Mb/s)**	**Min PUSCH (Mb/s)**	**Max PUSCH (Mb/s)**
COW 8 W	8.1	9.0	5.8	0.0	17.2
COW 40 W	8.8	7.9	7.2	0.0	19.0
SCDA 5 W+ PSCR MN	9.5	9.3	1.9	5.3	13.3
SCDA 5 W + COW 8 W+ PSCR MN	8.0	9.8	3.8	1.3	13.3
SCDA 5 W + COW 40 W + PSCR MN	11.0	11.1	1.3	6.8	13.9

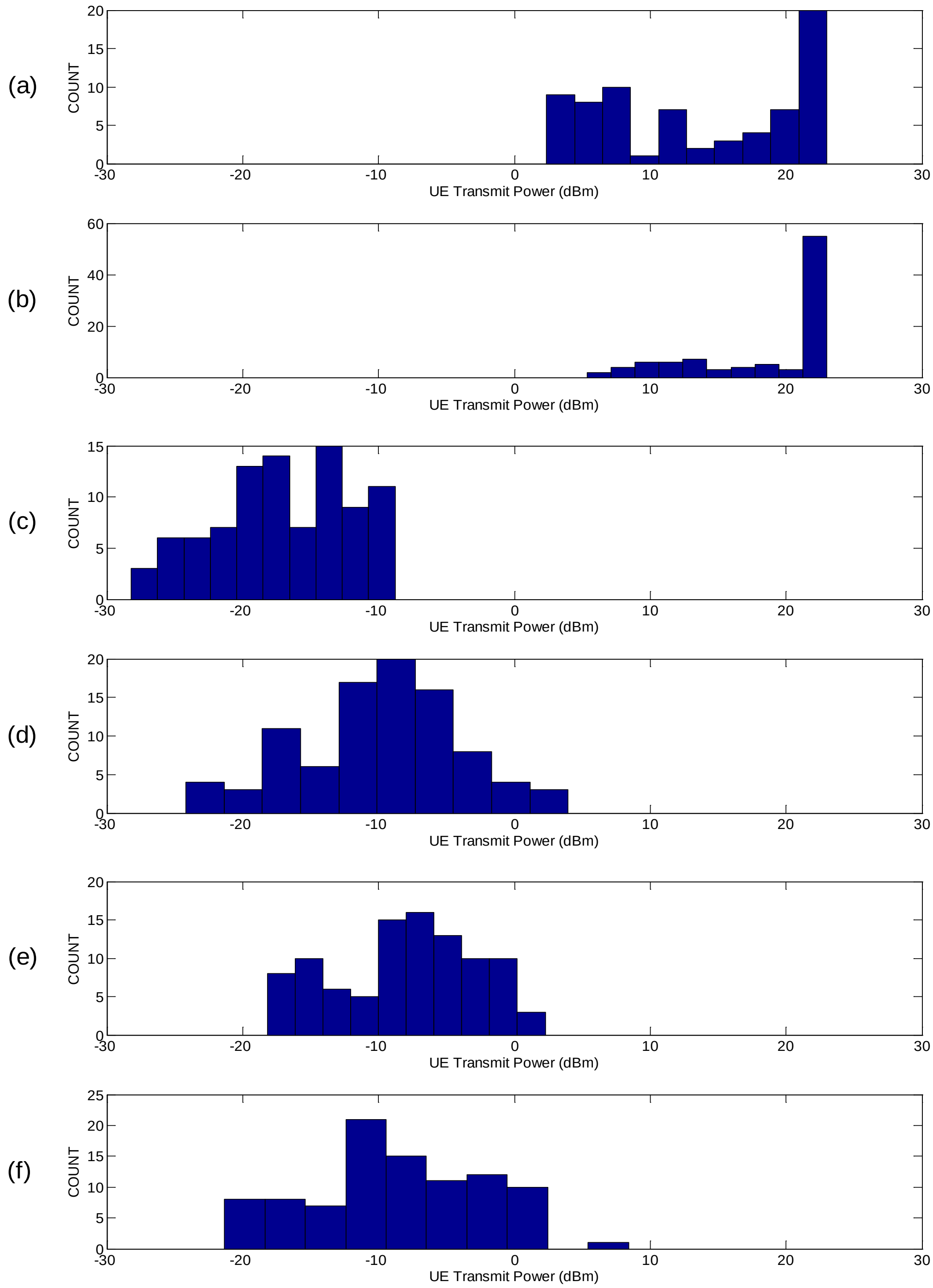

Figure 50. Level 2B histograms of UE transmit power for different coverage combinations with a TCP downlink data flow. (a) COW at 8 W (b) COW at 40 W, (c) small cell at 5 W with discrete antennas, (d) small cell at 5 W with discrete antennas and PSCR MN, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

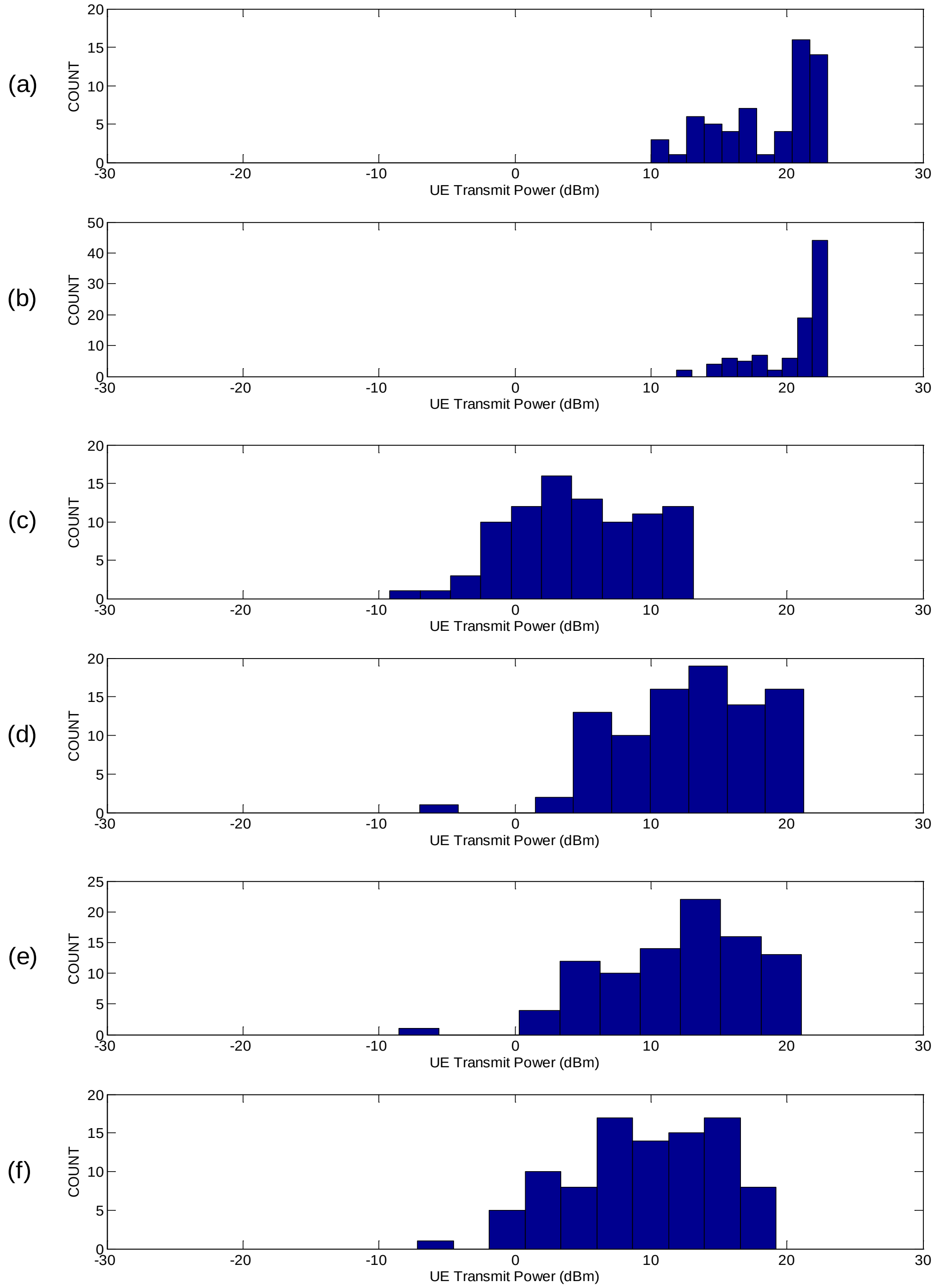

Figure 51. Level 2B histograms of UE transmit power for different coverage combinations with a TCP uplink data flow. (a) COW at 8 W (b) COW at 40 W, (c) small cell at 5 W with discrete antennas, (d) small cell at 5 W with discrete antennas and PSCR MN, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

Table 13. Level 2B UE transmit power statistics for a TCP downlink data flow.

Coverage Combination	Mean UEpwr (dBm)	Median UEpwr (dBm)	Standard Deviation (dBm)	Min UEpwr (dBm)	Max UEpwr (dBm)
COW 8 W	13.7	13.2	7.5	2.4	23.0
COW 40 W	18.8	22.0	5.3	5.4	23.0
SCDA 5 W	-17.0	-17.3	4.9	-28.2	-8.8
SCDA 5 W+ PSCR MN	-10.0	-9.5	6.0	-24.2	4.0
SCDA 5 W + COW 8 W+ PSCR MN	-7.8	-6.9	5.3	-18.2	2.3
SCDA 5 W + COW 40 W + PSCR MN	-8.5	-8.7	6.5	-21.3	8.4

Table 14. Level 2B UE transmit power statistics for a TCP uplink data flow.

Coverage Combination	Mean UEpwr (dBm)	Median UEpwr (dBm)	Standard Deviation (dBm)	Min UEpwr (dBm)	Max UEpwr (dBm)
COW 8 W	18.4	20.4	3.8	10.0	23.0
COW 40 W	20.5	21.7	2.7	11.9	23.0
SCDA 5 W	4.7	4.7	5.0	-9.2	13.1
SCDA 5 W+ PSCR MN	12.8	13.3	5.3	-7.0	21.2
SCDA 5 W + COW 8 W+ PSCR MN	12.0	13.1	5.5	-8.5	21.0
SCDA 5 W + COW 40 W + PSCR MN	9.6	10.0	5.5	-7.2	19.2

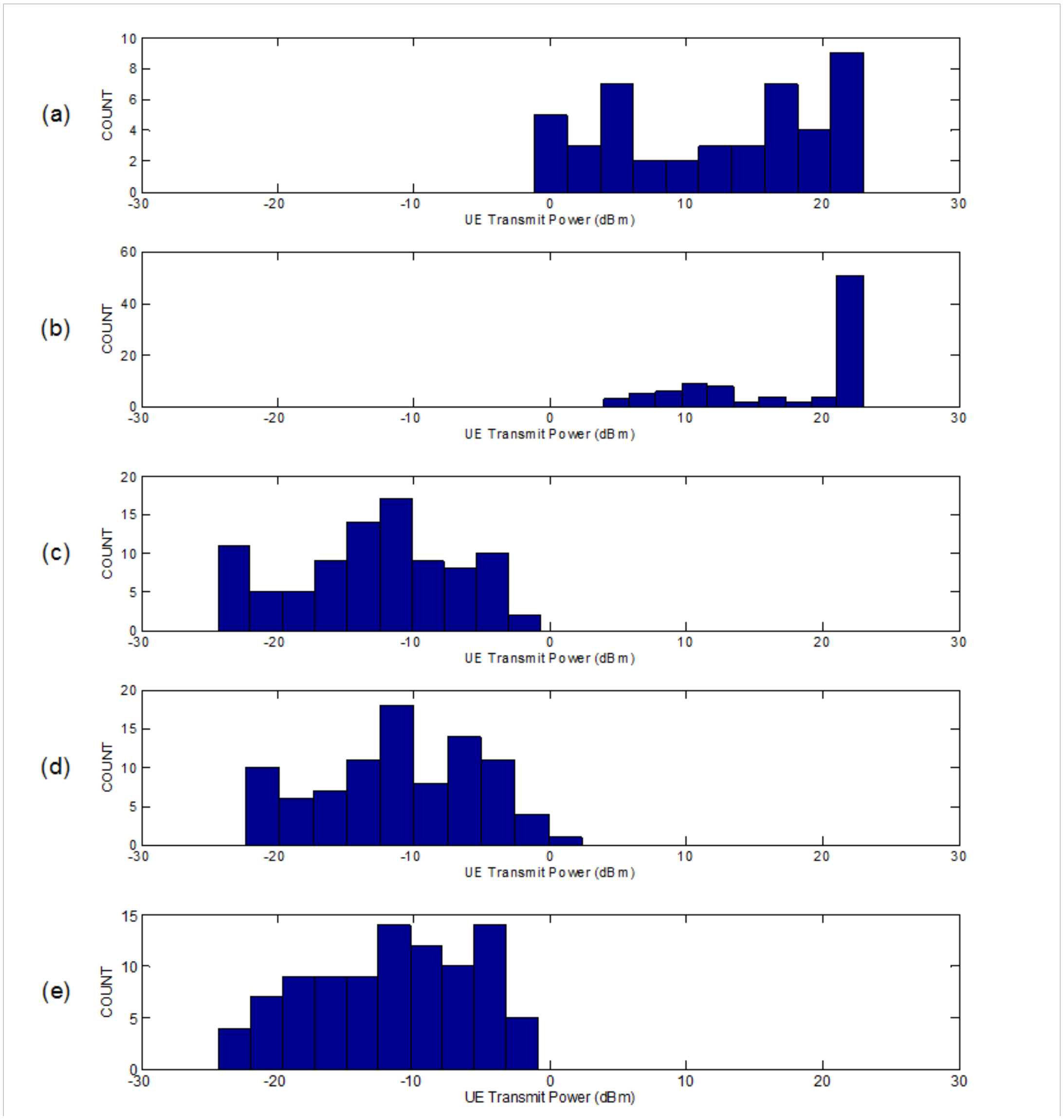

Figure 52. Level 2B histograms of UE transmit power for different coverage combinations with a UDP downlink data flow. (a) COW at 8 W, (b) COW at 40 W, (c) small cell at 5 W with discrete antennas and PSCR MN, (d) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

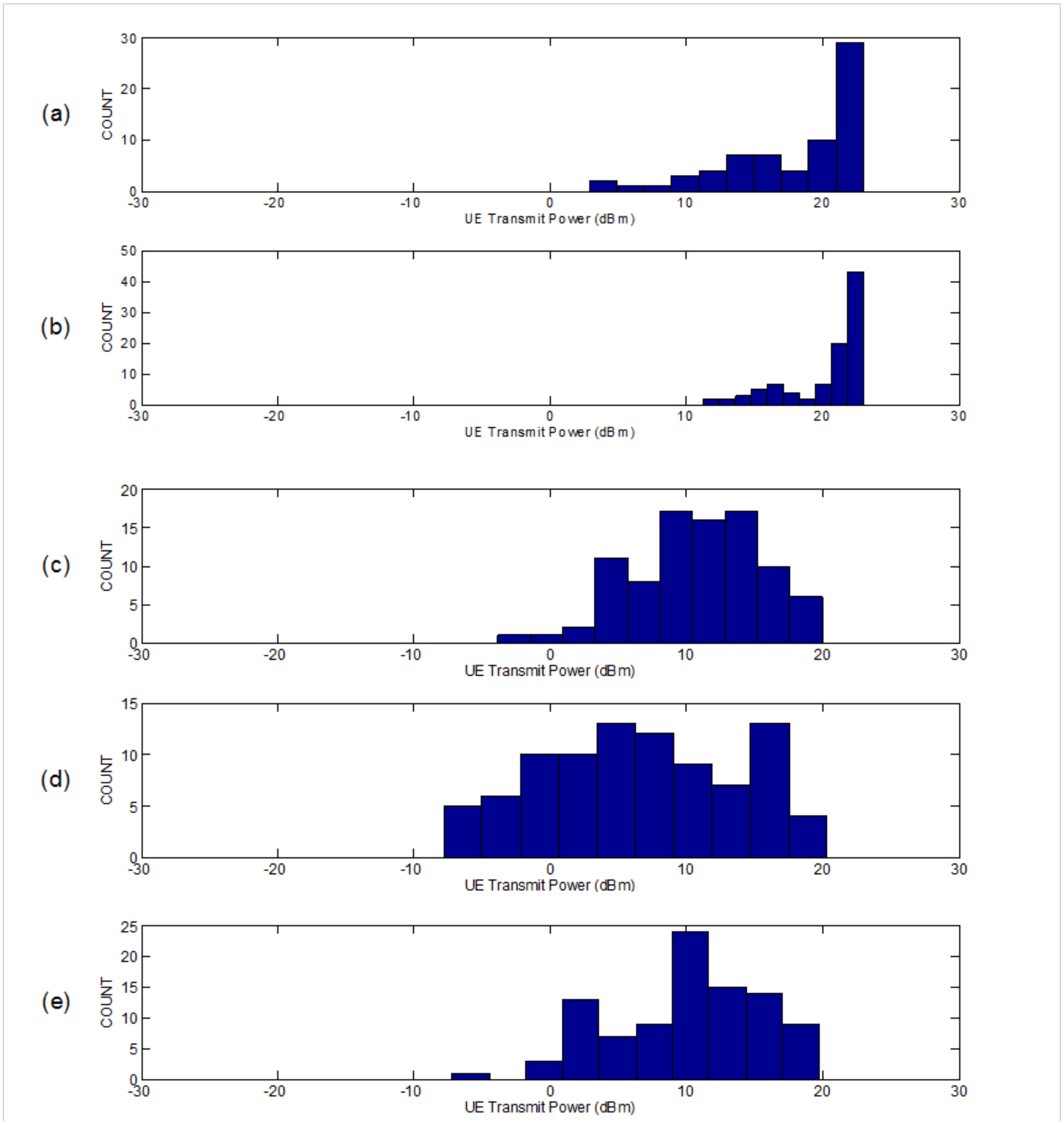

Figure 53. Level 2B histograms of UE transmit power for different coverage combinations with a UDP uplink data flow. (a) COW at 8 W, (b) COW at 40 W, (c) small cell at 5 W with discrete antennas and PSCR MN, (d) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

Table 15. Level 2B UE transmit power statistics for a UDP downlink data flow.

Coverage Combination	**Mean UEpwr (dBm)**	**Median UEpwr (dBm)**	**Standard Deviation (dBm)**	**Min UEpwr (dBm)**	**Max UEpwr (dBm)**
COW 8 W	12.3	14.5	8.1	-1.1	23.0
COW 40 W	17.7	21.3	6.2	3.9	23.0
SCDA 5 W+ PSCR MN	-12.8	-12.3	6.0	-24.4	-0.7
SCDA 5 W + COW 8 W+ PSCR MN	-11.0	-10.7	5.9	-22.3	2.4
SCDA 5 W + COW 40 W + PSCR MN	-11.5	-11.2	5.9	-24.3	-0.9

Table 16. Level 2B UE transmit power statistics for a UDP uplink data flow.

Coverage Combination	**Mean UEpwr (dBm)**	**Median UEpwr (dBm)**	**Standard Deviation (dBm)**	**Min UEpwr (dBm)**	**Max UEpwr (dBm)**
COW 8 W	17.9	20.1	5.0	2.9	23.0
COW 40 W	20.2	21.3	3.0	11.3	23.0
SCDA 5 W+ PSCR MN	10.8	10.8	4.7	-3.8	20.0
SCDA 5 W + COW 8 W+ PSCR MN	6.4	6.3	7.1	-7.8	20.3
SCDA 5 W + COW 40 W + PSCR MN	10.2	10.8	5.5	-7.2	19.8

3.2 Level 1B Measured Results

Level 1B is located on the ground level of the DLC. On this floor, the PSCR MN provides somewhat better coverage than on level 2B, but is still intermittent and very unreliable. Connectivity can be achieved in some spots but it is quickly lost during walk testing, and the connection between the UE and the macro network is dropped. We could only achieve reliable connectivity using either the SCDA or a COW parked outside the building. We used the same in-building coverage configurations that were used on level 2B with the addition of the SCDAS system described earlier in Section 2.4.4. The SCDAS system was not used in combination with either the PSCR MN or the COW due to tight time constraints. Results were obtained once again for both uplink and downlink data flows using both TCP and UDP.

Results were obtained on level 1B for the following seven coverage combinations:

- SCDA only with 5 W input
- COW only at 8 W
- COW only at 40 W
- PSCR MN + SCDA with 5 W input
- PSCR MN +SCDA at 5 W + COW at 40 W

- PSCR MN + SCDA at 5 W + COW at 8 W
- Four-antenna SCDAS

Serving cell RSRP results superimposed on the level 1 floor plan are shown in Figures 54–60 for a TCP downlink data flow. Comparative histograms of the serving cell RSRP are given for the four uplink and downlink data flows with TCP and UDP given in Figures 61–64. The associated statistical results are summarized in Tables 17–20.

When the COW alone is providing coverage, maximum signal levels occur on the eastern side of the DLC, where the COW is located. The lowest signal levels occur on the west side of the DLC due primarily to the blockage effects of the interior walls. At 40 W, the coverage improves significantly with roughly a 10 dB improvement at most interior points.

When the SCDA is active, coverage improves significantly. This effect is not only visible in the floor plan of Figure 56, but it is even more pronounced in the comparative RSRP histograms of Figures 61–64, where a significant shift occurs in the distributions with the SCDA system on the air. The picture does not change much with the COW and PSCR MN added to the coverage. Clearly, the SCDA dominates the interior coverage.

The best signal levels are realized with the small cell feeding the four-antenna SCDAS system. This improvement is quite visible in the histograms where an increase of typically 5–10 dB is noted. This result comes as no surprise because the DAS is designed to minimize path loss between the small cell and the UE through the use of multiple antennas [7], [8].

The corresponding CINR histograms are plotted in Figures 65–68 with summary statistics provided in Tables 21–24. The largest spread of CINR values occurs with the COW operating at a transmit power level of 8 W. The highest CINR values are seen on the east side of DLC, where the signals are strongest. Minimum values are seen on the west side of the DLC where the path losses are highest. Large variations in CINR are also seen when the SCDA system is used in conjunction with the COW at either 8 W or 40 W power levels. A reduction in CINR levels occurs in this case due to increased interference levels, since the COW is functioning as a neighbor cell over most of walk path. The best signal-to-noise characteristics are realized with DAS system active, due to the combination of reduced path losses and other coverage elements being off the air (COW, PSCR MN).

The PDSCH results are shown in Figures 69 and 71 for TCP and UDP respectively. The corresponding statistical results are summarized in Tables 25 and 27. As can be seen in Figures 69(e) and 71(e), the SCDAS system clearly provides the highest performance level, with the majority of measured data rates in excess of 30 Mb/s. A lower level of performance is seen with COW-only coverage at both the 8 W and 40 W transmit power levels. This is due to the higher path losses caused by the building structure.

Significantly degraded data rate performance is seen when the combination of the SCDA, the COW (40 W), and the PSCR MN are active (Figures 69(f) and 71(f)). This is due to the so-called “ping pong” effect in which multiple handovers occur between the COW and the small cell on the east side of the DLC. The handovers significantly reduce the downlink data rates when the data flow to the UE is alternately switching back and forth between the small cell and the COW.

This could be remedied, and the system performance greatly improved, by optimizing the hysteresis and offset parameters on both the small cell and the COW. We decided to use the vendor-supplied parameters for the PSCR MN eNB, small cell, and the COW eNB, due to tight testing time constraints. The observed effects demonstrate that increased RF coverage does not necessarily translate into higher data rates. System optimization is definitely required to achieve peak performance.

The TCP and UDP PUSCH uplink data rates are shown in Figures 70 and 72 respectively, with summary statistics given in Tables 26 and 28. In general, we see better performance with TCP than UDP. This is probably due to the guaranteed delivery properties of TCP. The best performance is realized with coverage provided by the SCDAS. Low data rates are noted for COW RF coverage, which is due to high path losses on the west side of the DLC. When we are using the SCDA system with UDP, we see frequent occurrences of low data rates (Figure 72 (c)), which are attributed to UE connectivity problems. This problem occurs occasionally in close proximity to an eNB. We also see reduced data rates due to handover ping pong effects when we use the SCDA system in conjunction with the COW. A comparison of Figures 70(e) and 70(f) with 72(e) and 72(f) reveals that this effect is much more pronounced for UDP than for TCP.

The UE transmit power levels are presented in Figures 73–76 and Tables 29–32 for downlink and uplink data flow using TCP and UDP. Several trends are apparent. First, the DAS system results in the lowest overall UE transmit power requirements. Second, the use of any of the in-building coverage combinations reduces the UE transmit power levels. Finally, the UE power level requirements are increased for uplink flows due to the increased data payload that must be transmitted.

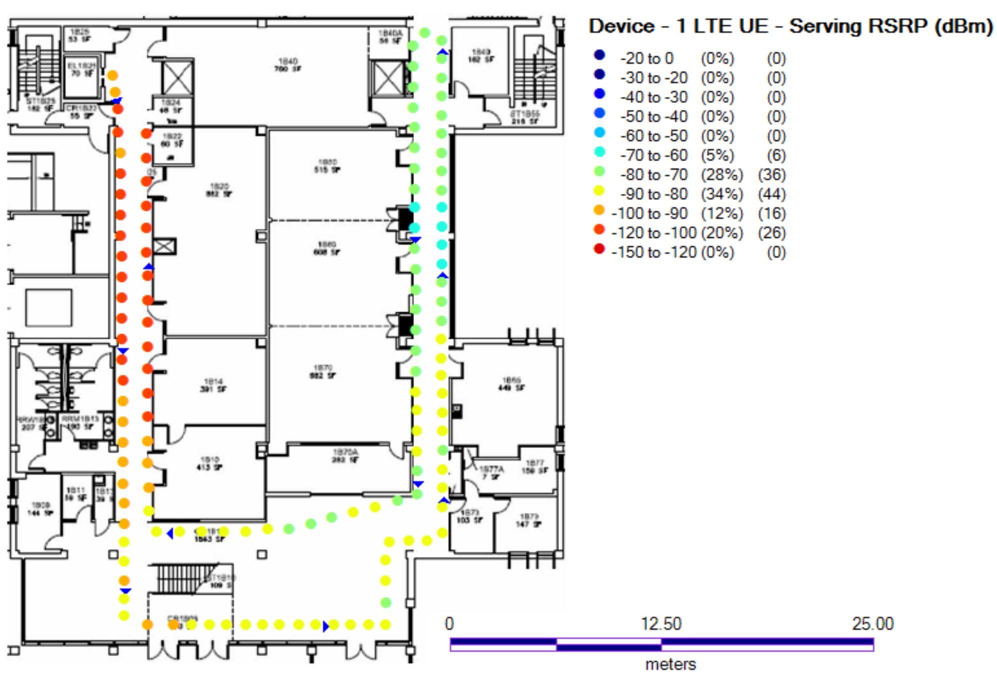

Figure 54. Level 1B reference signal received power (RSRP) for a TCP downlink data flow with the COW at 8 W. The top of the floor plan corresponds to north.

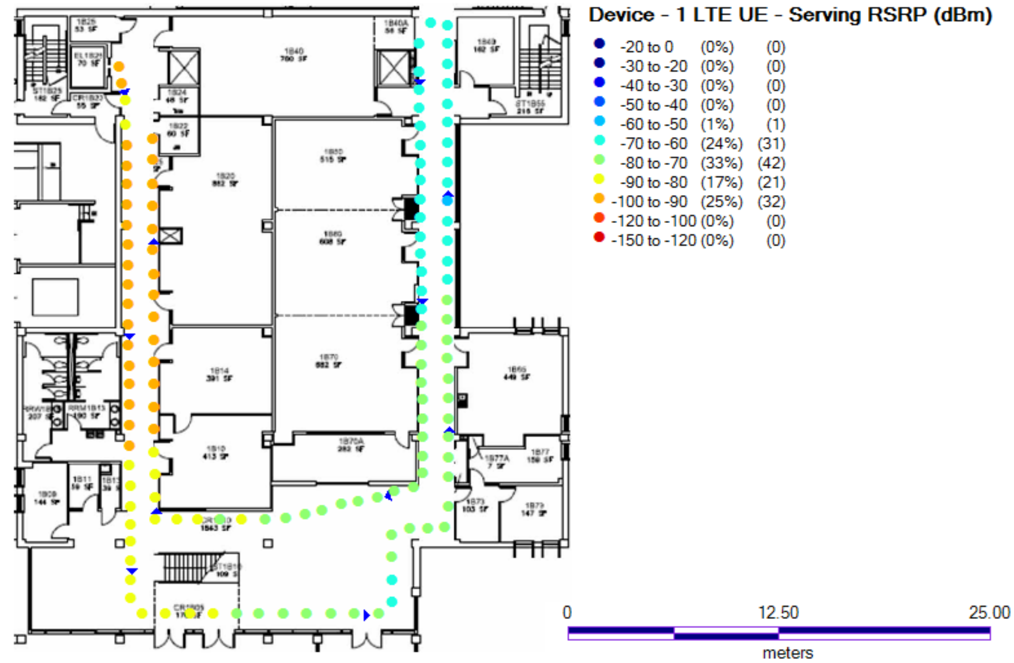

Figure 55 Level 1B reference signal received power (RSRP) for a TCP downlink data flow with the COW at 40 W. The top of the floor plan corresponds to north.

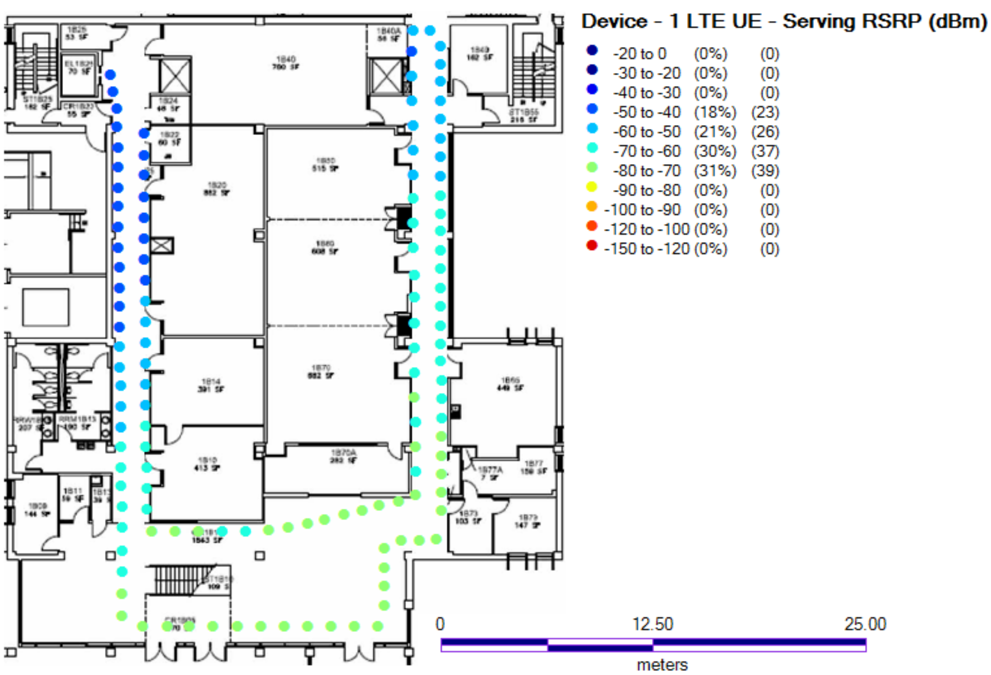

Figure 56 Level 1B reference signal received power (RSRP) for a TCP downlink data flow with the small cell at 5 W and discrete antennas. The direction of top of the floor plan is north.

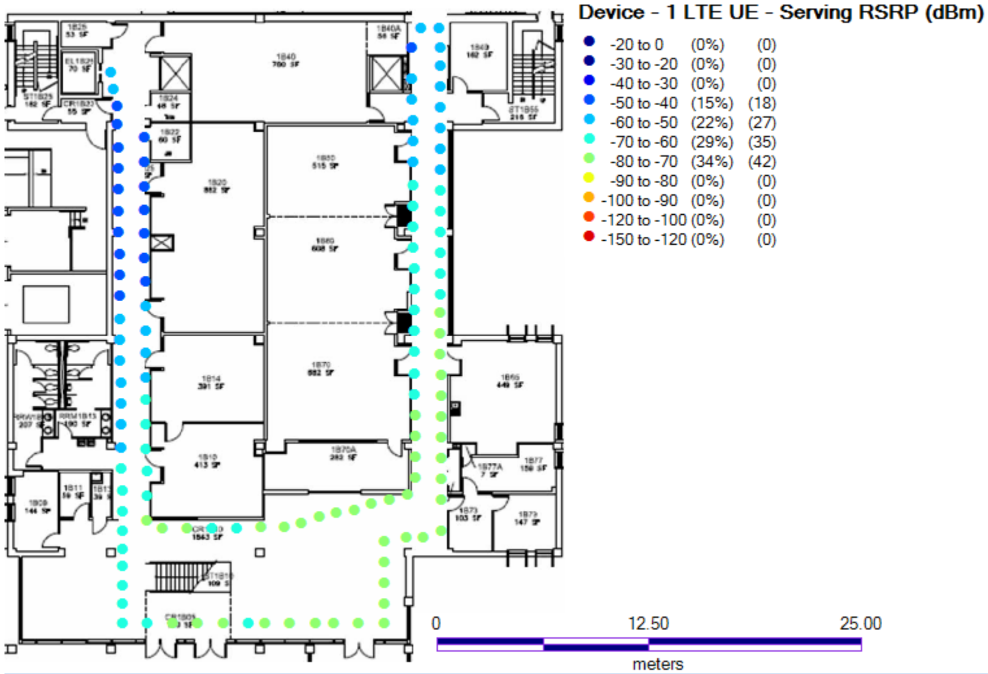

Figure 57. Level 1B reference signal received power (RSRP) for a TCP downlink data flow with the small cell at 5 W and the PSCR MN. The direction of top of the floor plan is north.

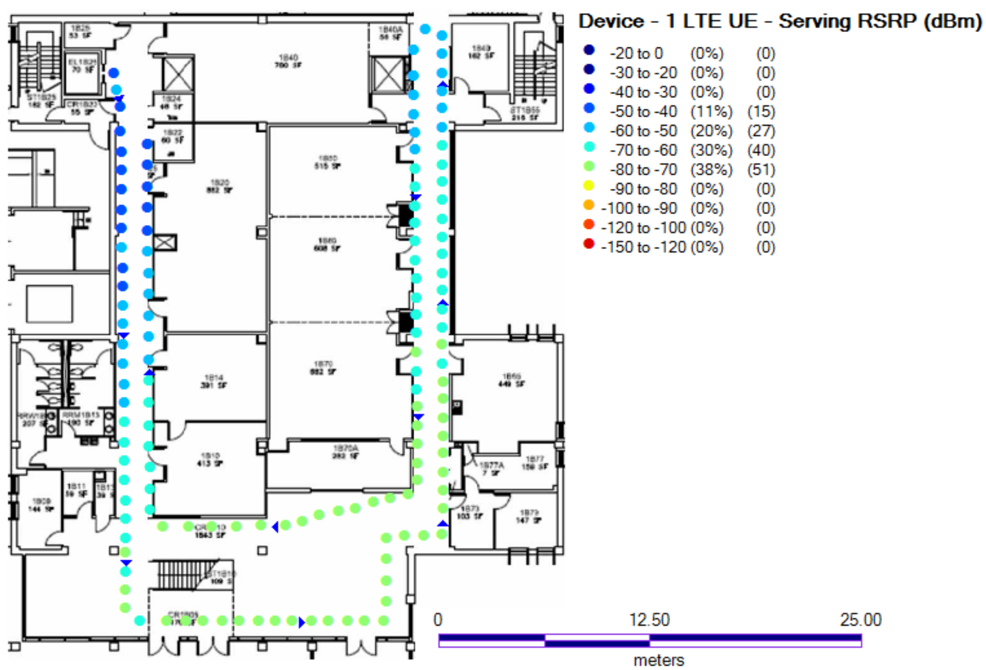

Figure 58. Level 1B reference signal received power (RSRP) for a TCP downlink data flow with the small cell at 5 W, COW at 8 W, and the PSCR MN. The direction of top of the floor plan is north.

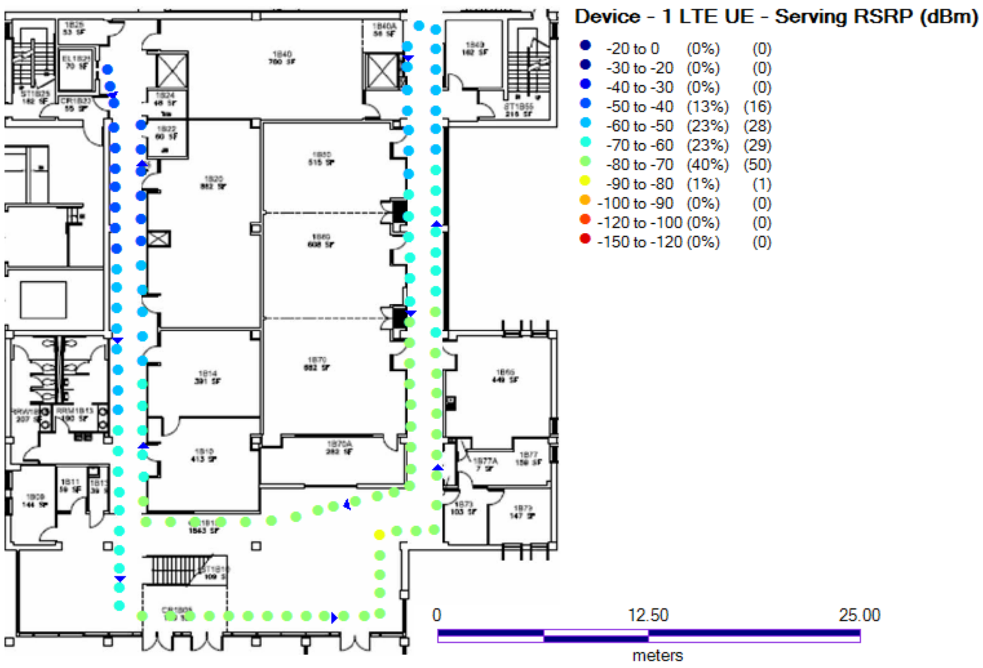

Figure 59. Level 1B reference signal received power (RSRP) for a TCP downlink data flow with the small cell at 5 W, COW at 40 W, and the PSCR MN. The direction of top of the floor plan is north.

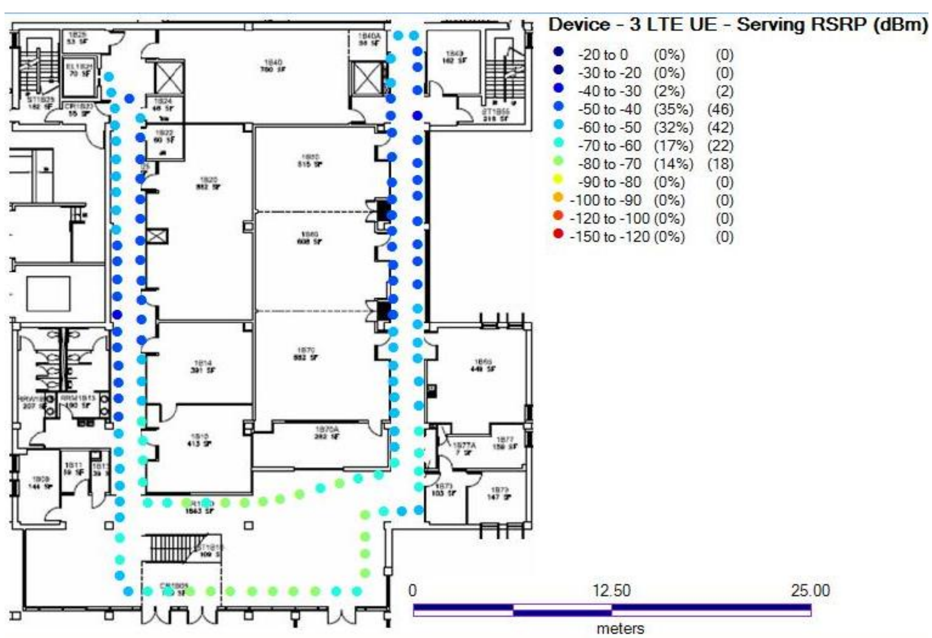

Figure 60. Level 1B reference signal received power (RSRP) for a TCP downlink data flow with the small cell feeding a four-antenna DAS system. The direction of top of the floor plan is north.

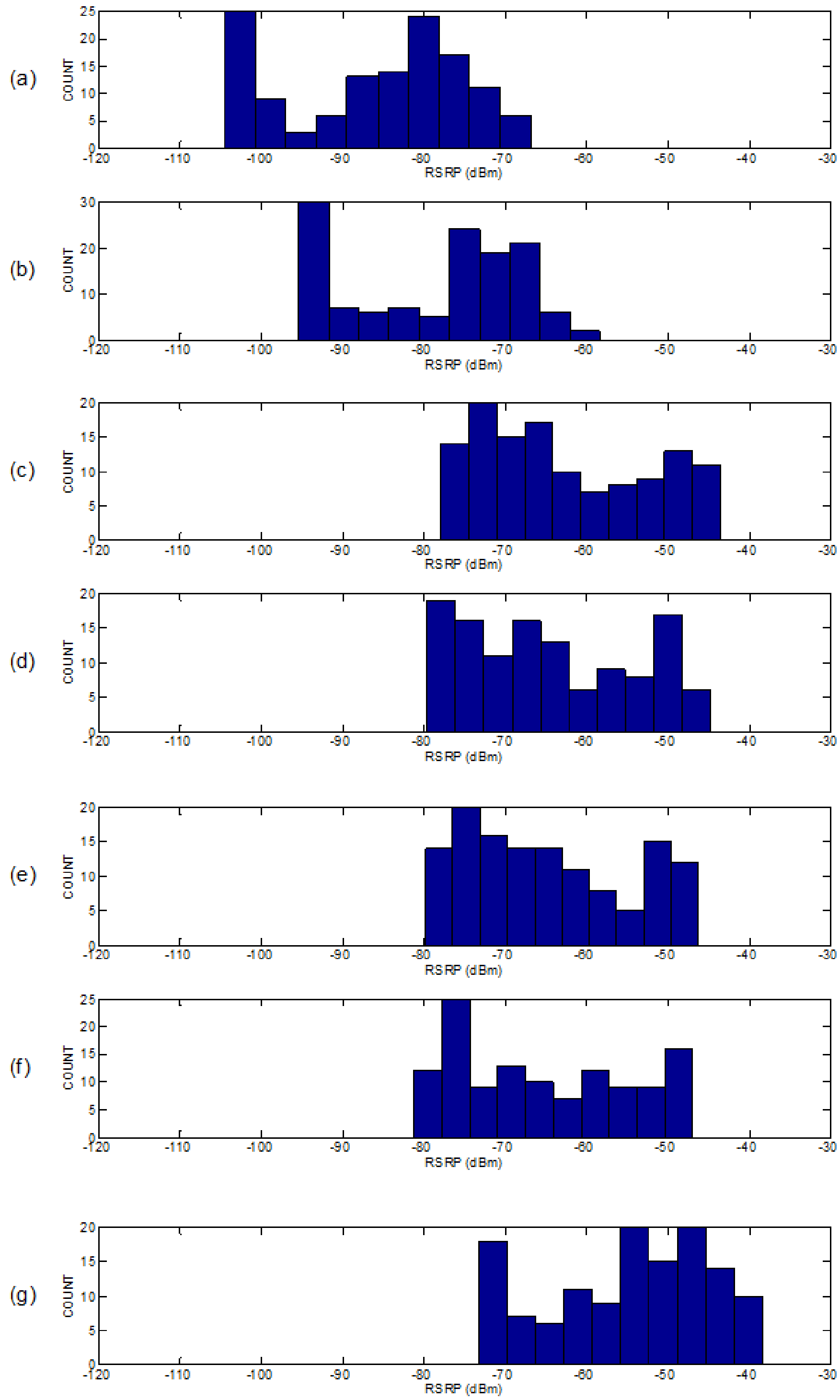

Figure 61. Level 1B histograms of RSRP for different coverage combinations with a TCP downlink data flow. (a) COW at 8 W, (b) COW at 40 W, (c) small cell at 5 W with discrete antennas, (d) small cell at 5 W with discrete antennas and PSCR MN, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (g) small cell feeding a four-antenna passive DAS system.

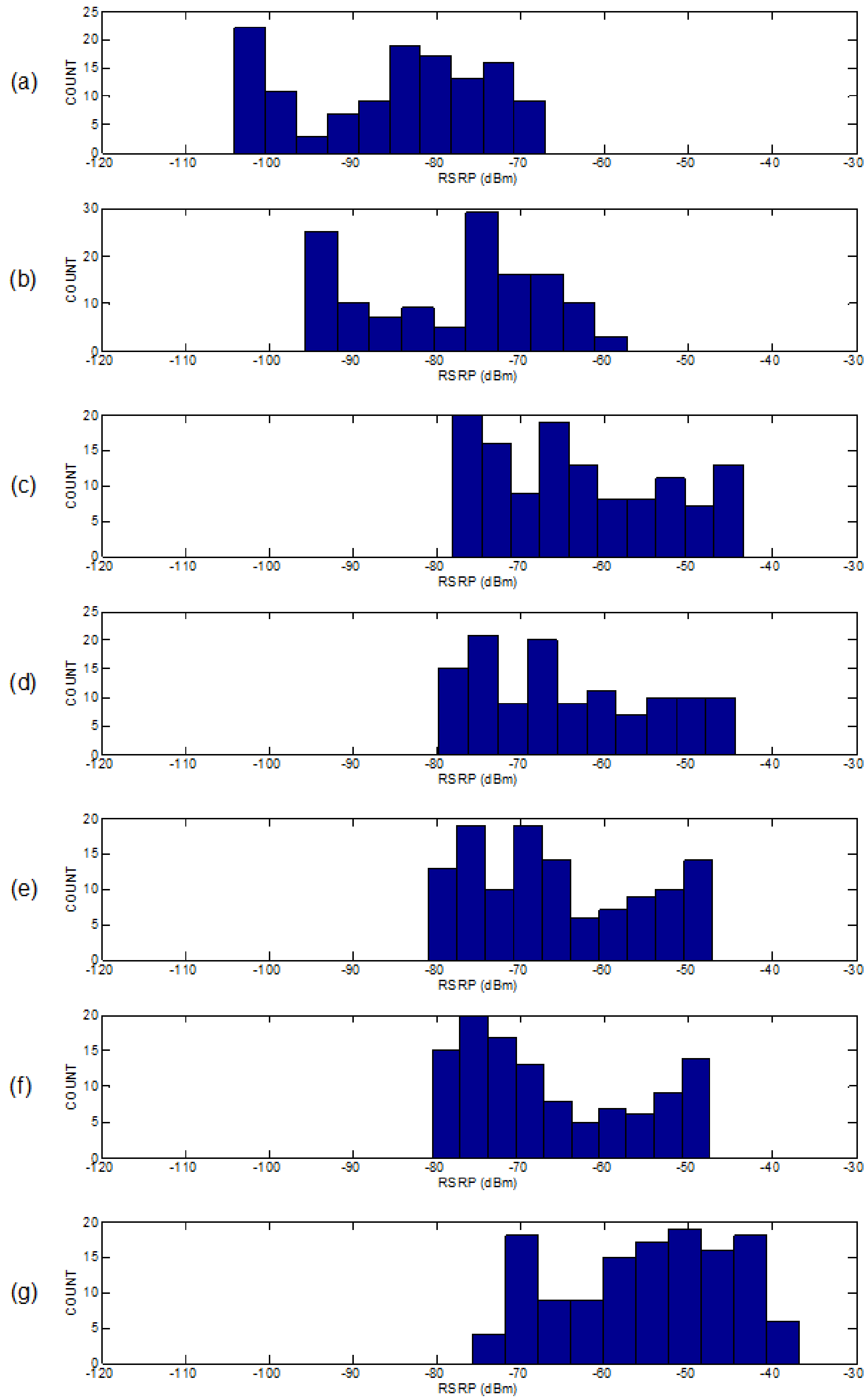

Figure 62. Level 1B histograms of RSRP for different coverage combinations with a TCP uplink data flow. (a) COW at 8 W, (b) COW at 40 W, (c) small cell at 5 W with discrete antennas, (d) small cell at 5 W with discrete antennas and PSCR MN, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (g) small cell feeding a four-antenna passive DAS system.

Table 17. Level 1B RSRP statistics for a TCP downlink data flow.

Coverage Combination	Mean RSRP (dBm)	Median RSRP (dBm)	Standard Deviation (dBm)	Min RSRP (dBm)	Max RSRP (dBm)
COW 8 W	-86.2	-83.8	10.9	-104.5	-66.9
COW 40 W	-78.7	-74.6	10.6	-95.5	-58.4
SCDA 5 W	-62.5	-65.2	10.4	-77.9	-43.6
SCDA 5 W+ PSCR MN	-64.2	-66.4	10.3	-79.6	-44.7
SCDA 5 W + COW 8 W+ PSCR MN	-64.8	-63.4	10.0	-79.8	-46.3
SCDA 5 W + COW 40 W + PSCR MN	-65.3	-66.5	10.3	-81.2	-47.0
SCDAS	-54.8	-52.8	10.0	-73.4	-38.3

Table 18. Level 1B RSRP statistics for a TCP uplink data flow.

Coverage Combination	Mean RSRP (dBm)	Median RSRP (dBm)	Standard Deviation (dBm)	Min RSRP (dBm)	Max RSRP (dBm)
COW 8 W	-85.5	-83.9	11.0	-104.2	-67.2
COW 40 W	-78.3	-75.0	10.8	-95.8	-57.3
SCDA 5 W	-63.0	-64.6	10.3	-78.2	-43.5
SCDA 5 W+ PSCR MN	-64.4	-67.1	10.4	-79.9	-44.4
SCDA 5 W + COW 8 W+ PSCR MN	-65.5	-67.8	10.1	-81.0	-47.2
SCDA 5 W + COW 40 W + PSCR MN	-66.5	-69.0	10.3	-80.6	-47.5
SCDAS	-54.9	-53.1	10.0	-75.8	-36.8

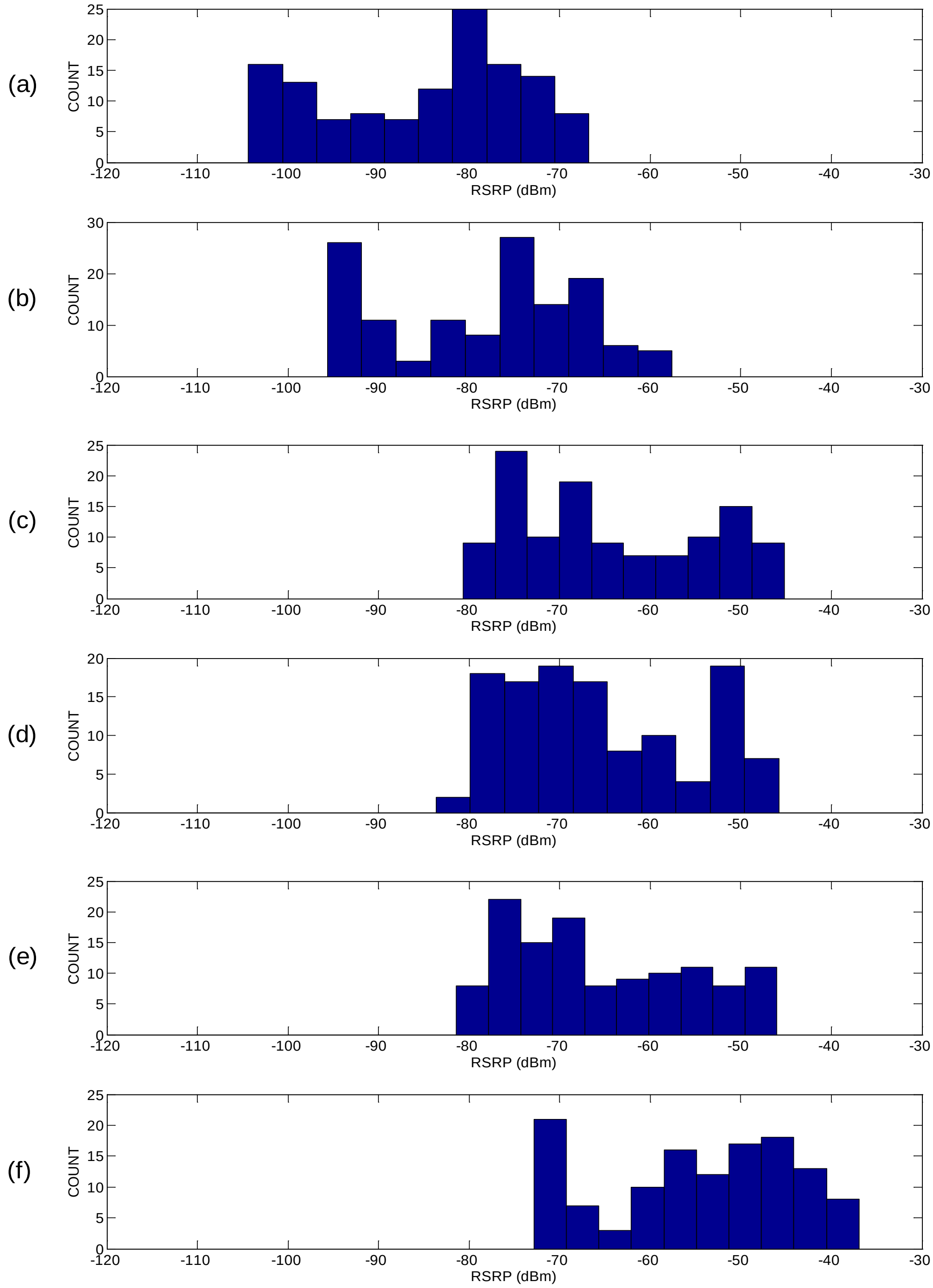

Figure 63. Level 1B histograms of RSRP for different coverage combinations with a UDP downlink data flow. (a) COW at 8 W, (b) COW at 40 W, (c) small cell at 5 W with discrete antennas and PSCR MN, (d) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (f) small cell feeding a four-antenna passive DAS system.

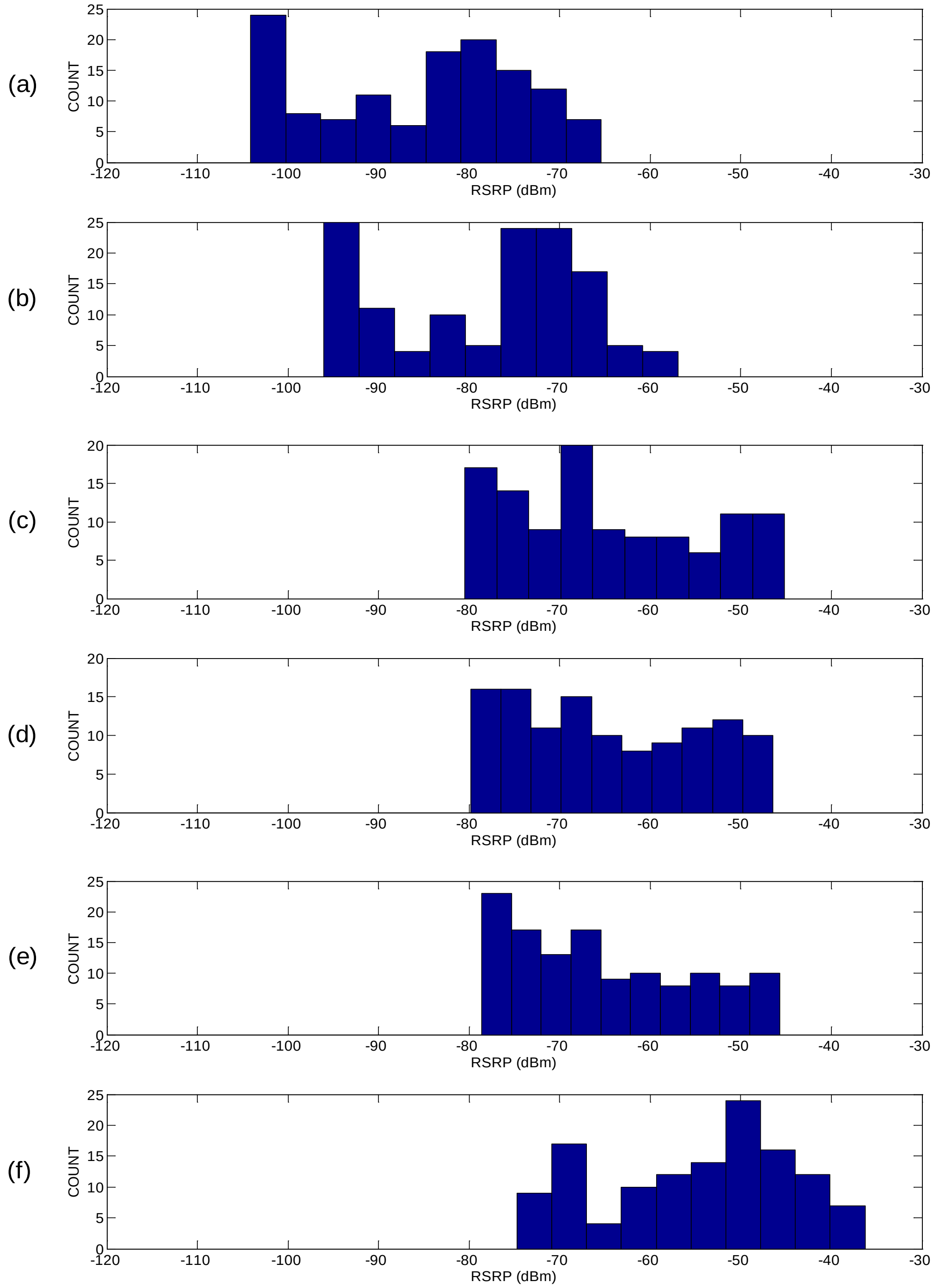

Figure 64. Level 1B histograms of RSRP for different coverage combinations with a UDP uplink data flow. (a) COW at 8 W, (b) COW at 40 W, (c) small cell at 5 W with discrete antennas and PSCR MN , (d) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (f) small cell feeding a four-antenna passive DAS system.

Table 19. Level 1B RSRP statistics for a UDP downlink data flow.

Coverage Combination	**Mean RSRP (dBm)**	**Median RSRP (dBm)**	**Standard Deviation (dBm)**	**Min RSRP (dBm)**	**Max RSRP (dBm)**
COW 8 W	-85.0	-81.7	10.7	-104.4	-66.8
COW 40 W	-78.6	-75.8	10.7	-95.7	-57.6
SCDA 5 W+ PSCR MN	-64.4	-66.8	10.4	-80.7	-45.2
SCDA 5 W + COW 8 W + PSCR MN	-65.4	-67.8	9.8	-83.7	-45.8
SCDA 5 W + COW 40 W + PSCR MN	-65.3	-67.9	10.1	-81.4	-46.0
SCDAS	-54.5	-53.1	10.4	-72.9	-36.9

Table 20. Level 2B RSRP statistics for a UDP uplink data flow.

Coverage Combination	**Mean RSRP (dBm)**	**Median RSRP (dBm)**	**Standard Deviation (dBm)**	**Min RSRP (dBm)**	**Max RSRP (dBm)**
COW 8 W	-85.4	-82.8	11.2	-104.1	-65.4
COW 40 W	-78.2	-74.2	10.9	-96.1	-56.9
SCDA 5 W+ PSCR MN	-64.9	-67.6	10.5	-80.5	-45.2
SCDA 5 W + COW 8 W+ PSCR MN	-64.5	-65.5	10.0	-79.8	-46.4
SCDA 5 W + COW 40 W + PSCR MN	-65.1	-67.7	9.7	-78.6	-45.7
SCDAS	-54.7	-52.5	10.1	-74.7	-36.3

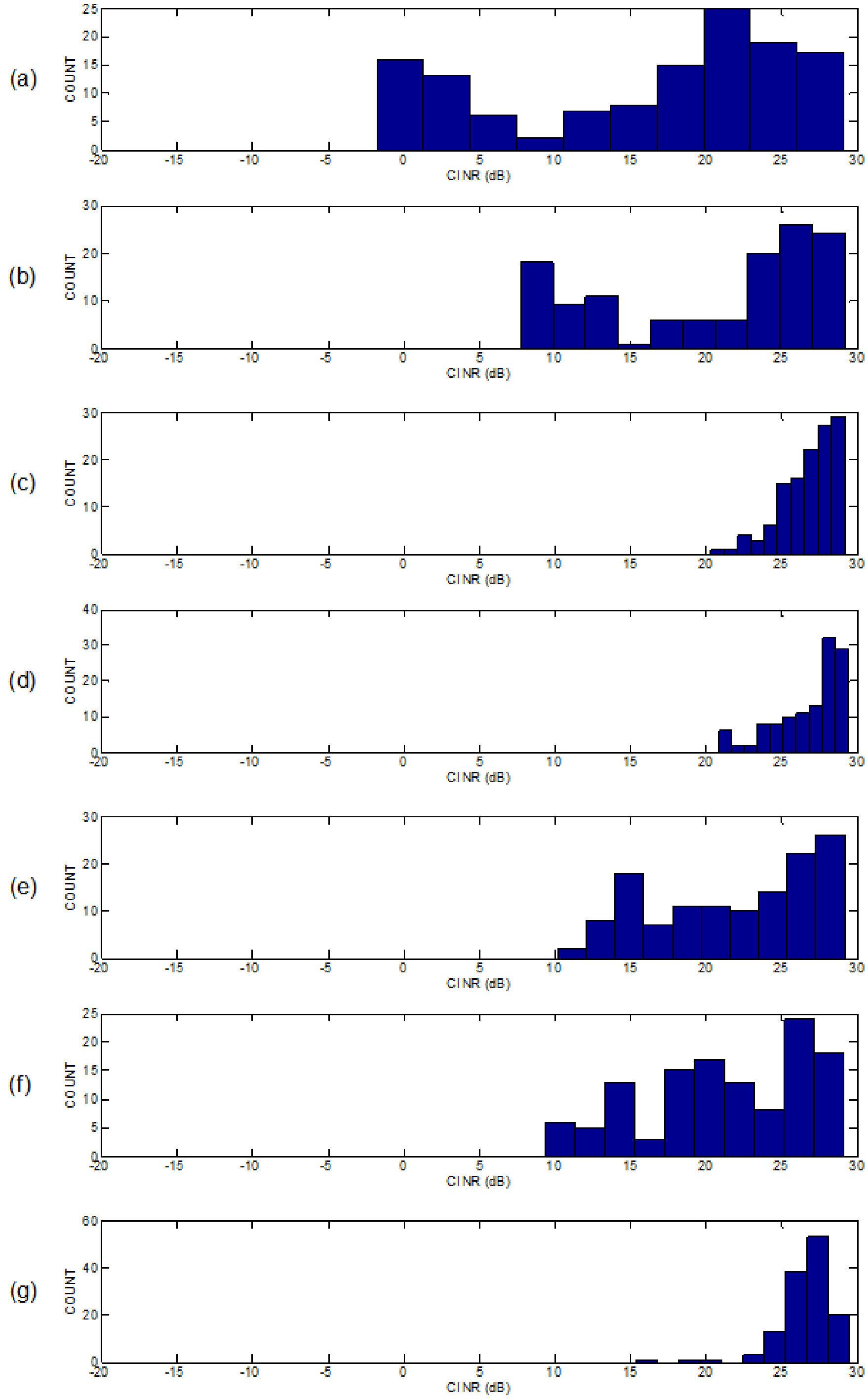

Figure 65. Level 1B histograms of CINR for different coverage combinations with a TCP downlink data flow. (a) COW at 8 W, (b) COW at 40 W, (c) small cell at 5 W with discrete antennas, (d) small cell at 5 W with discrete antennas and PSCR MN, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (g) small cell feeding a four-antenna passive DAS system.

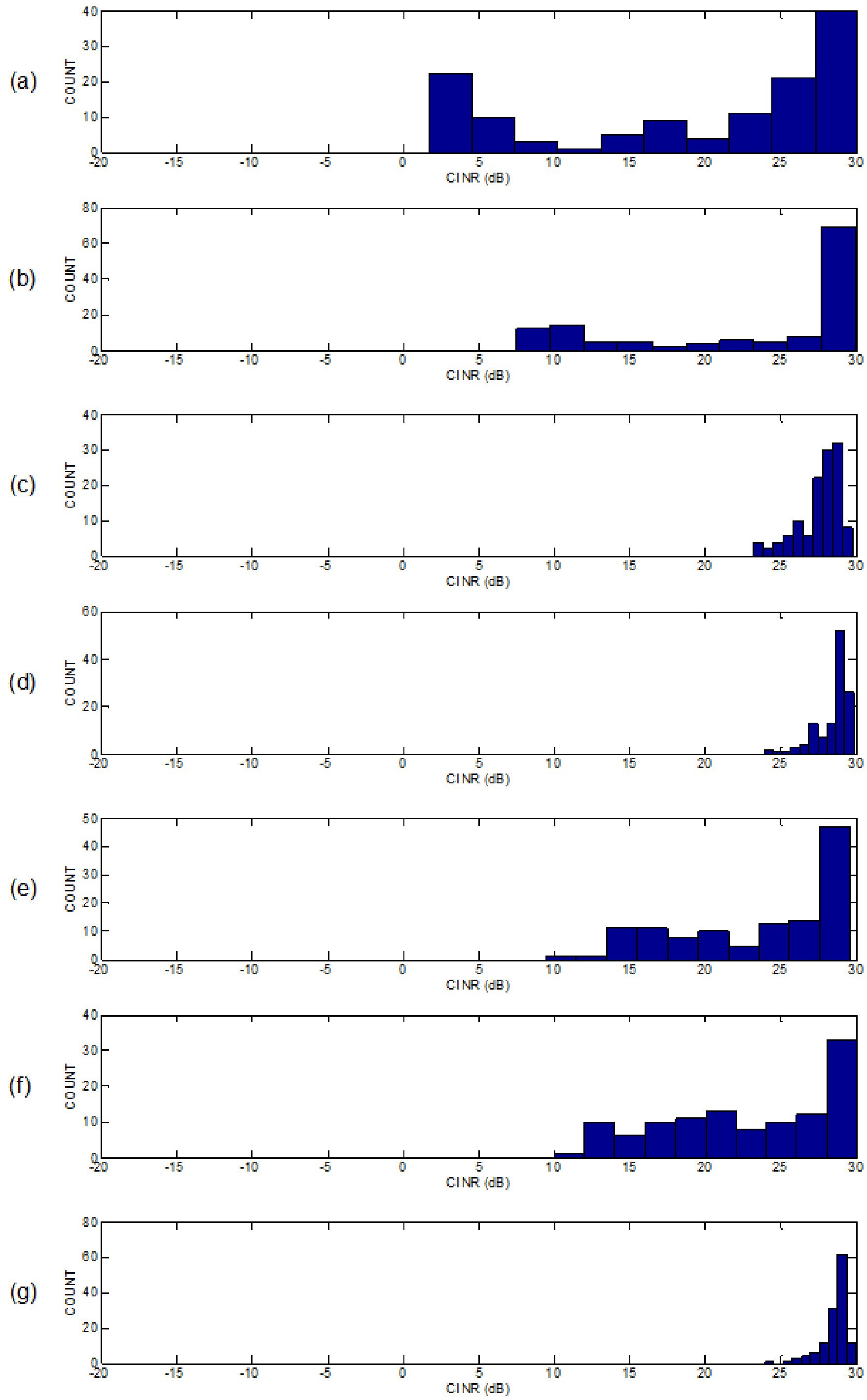

Figure 66. Level 1B histograms of CINR for different coverage combinations with a TCP uplink data flow. (a) COW at 8 W, (b) COW at 40 W, (c) small cell at 5 W with discrete antennas, (d) small cell at 5 W with discrete antennas and PSCR MN, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (g) small cell feeding a four-antenna passive DAS system.

Table 21. Level 1B CINR statistics for a TCP downlink data flow.

Coverage Combination	**Mean CINR (dBm)**	**Median CINR (dBm)**	**Standard Deviation (dBm)**	**Min CINR (dBm)**	**Max CINR (dBm)**
COW 8 W	15.8	19.3	9.7	-1.8	29.1
COW 40 W	20.4	24.0	7.2	7.7	29.2
SCDA 5 W	26.8	27.2	1.8	20.3	29.2
SCDA 5 W+ PSCR MN	26.8	27.7	2.2	20.9	29.4
SCDA 5 W + COW 8 W+ PSCR MN	22.0	23.2	5.3	10.2	29.2
SCDA 5 W + COW 40 W + PSCR MN	21.3	22.2	5.4	9.3	29.1
SCDAS	26.6	26.7	1.8	15.4	29.5

Table 22. Level 1B CINR statistics for a TCP uplink data flow.

Coverage Combination	**Mean CINR (dBm)**	**Median CINR (dBm)**	**Standard Deviation (dBm)**	**Min CINR (dBm)**	**Max CINR (dBm)**
COW 8 W	19.2	23.7	9.9	1.7	30.1
COW 40 W	22.8	27.9	7.8	7.5	30.0
SCDA 5 W	27.6	27.9	1.4	23.2	29.8
SCDA 5 W+ PSCR MN	28.5	28.9	1.2	23.9	29.8
SCDA 5 W + COW 8 W+ PSCR MN	23.8	25.6	5.3	9.4	29.6
SCDA 5 W + COW 40 W + PSCR MN	22.7	23.4	5.6	10.0	30.1
SCDAS	28.6	28.8	0.9	24.0	30.0

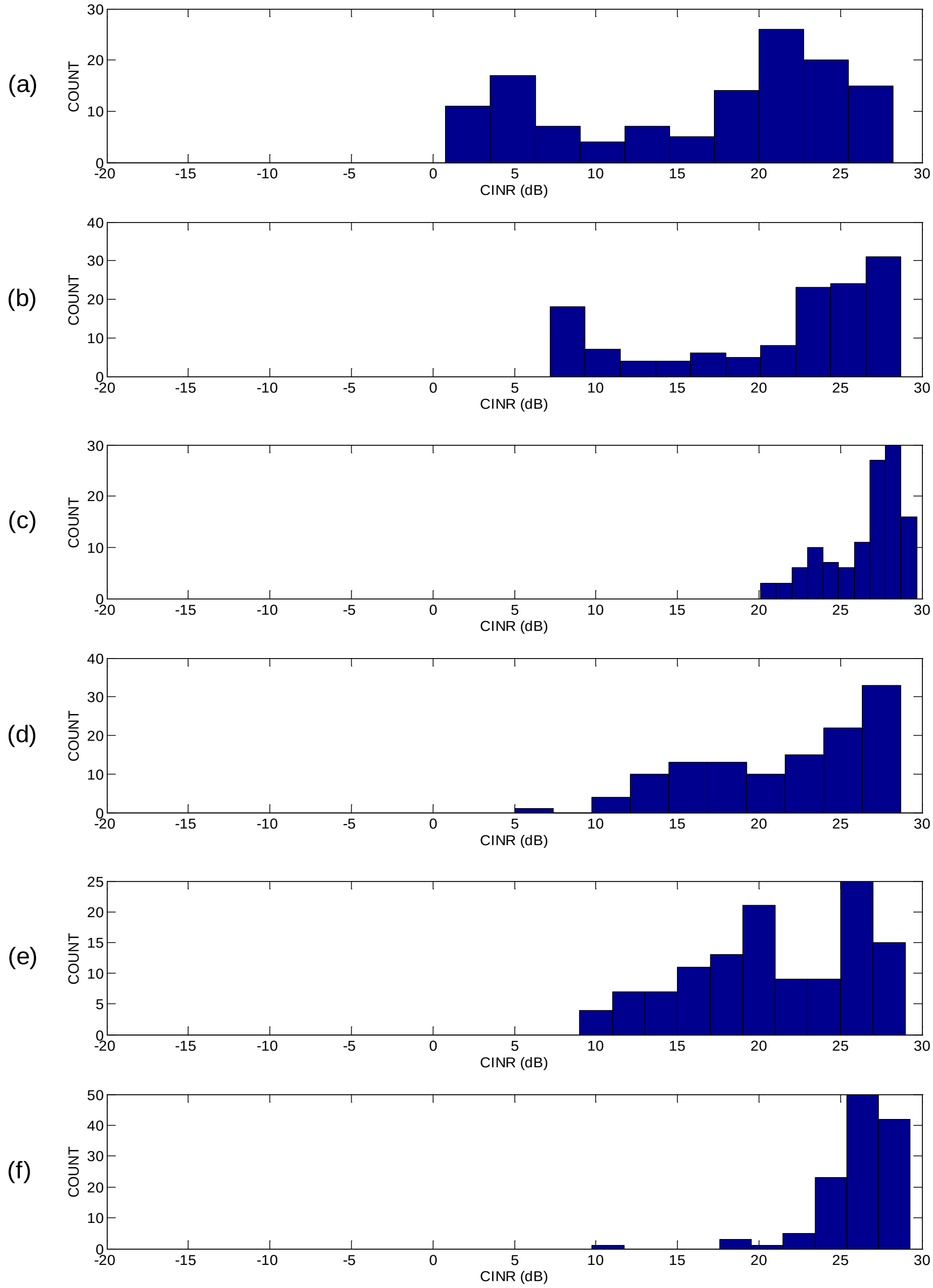

Figure 67. Level 1B histograms of CINR for different coverage combinations with a UDP downlink data flow. (a) COW at 8 W, (b) COW at 40 W, (c) small cell at 5 W with discrete antennas and PSCR MN, (d) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (f) small cell feeding a four-antenna passive DAS system.

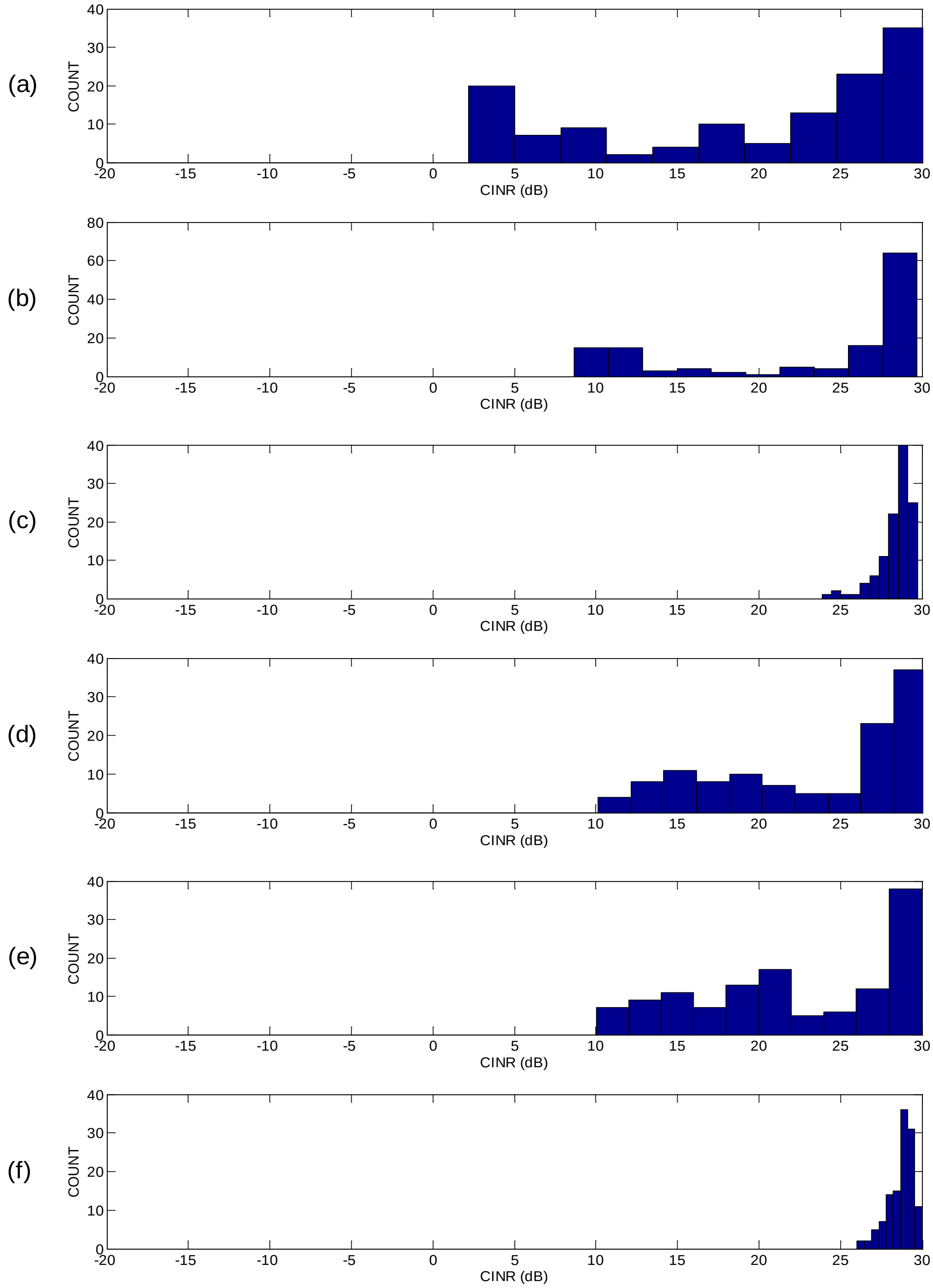

Figure 68. Level 1B histograms of CINR for different coverage combinations with a UDP uplink data flow. (a) COW at 8 W, (b) COW at 40 W, (c) small cell at 5 W with discrete antennas and PSCR MN , (d) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (f) small cell feeding a four-antenna passive DAS system.

Table 23. Level 1B CINR statistics for a UDP downlink data flow.

Coverage Combination	Mean CINR (dBm)	Median CINR (dBm)	Standard Deviation (dBm)	Min CINR (dBm)	Max CINR (dBm)
COW 8 W	16.5	19.6	8.4	0.8	28.2
COW 40 W	20.8	23.9	7.0	7.2	28.7
SCDA 5 W+ PSCR MN	26.5	27.3	2.3	20.1	29.7
SCDA 5 W + COW 8 W+ PSCR MN	21.7	22.9	5.4	5.0	28.7
SCDA 5 W + COW 40 W + PSCR MN	20.9	20.8	5.2	9.0	29.0
SCDAS	26.1	26.8	2.5	9.8	29.3

Table 24. Level 1B CINR statistics for a UDP uplink data flow.

Coverage Combination	Mean CINR (dBm)	Median CINR (dBm)	Standard Deviation (dBm)	Min CINR (dBm)	Max CINR (dBm)
COW 8 W	19.5	24.0	9.5	2.2	30.4
COW 40 W	23.0	27.6	7.6	8.7	29.7
SCDA 5 W+ PSCR MN	28.4	28.7	1.1	23.9	29.7
SCDA 5 W + COW 8 W+ PSCR MN	23.2	26.4	6.0	10.1	30.3
SCDA 5 W + COW 40 W + PSCR MN	22.2	21.8	6.1	10.1	30.0
SCDAS	28.7	28.9	0.8	26.0	30.5

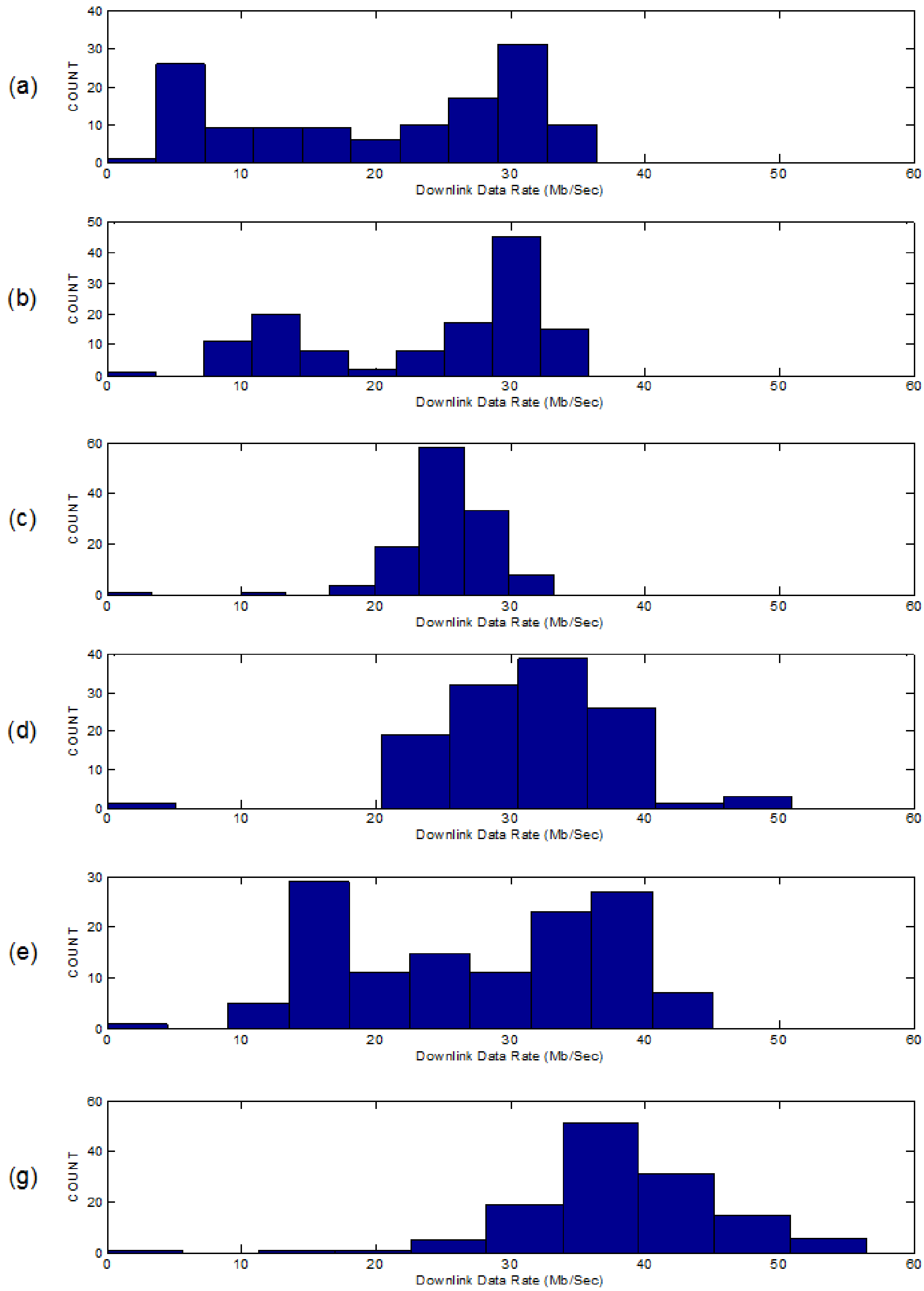

Figure 69. Level 1B histograms of PDSCH for different coverage combinations with a TCP downlink data flow. (a) COW at 8 W, (b) COW at 40 W, (c) small cell at 5 W with discrete antennas, (d) small cell at 5 W with discrete antennas and PSCR MN, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (g) small cell feeding a four-antenna passive DAS system.

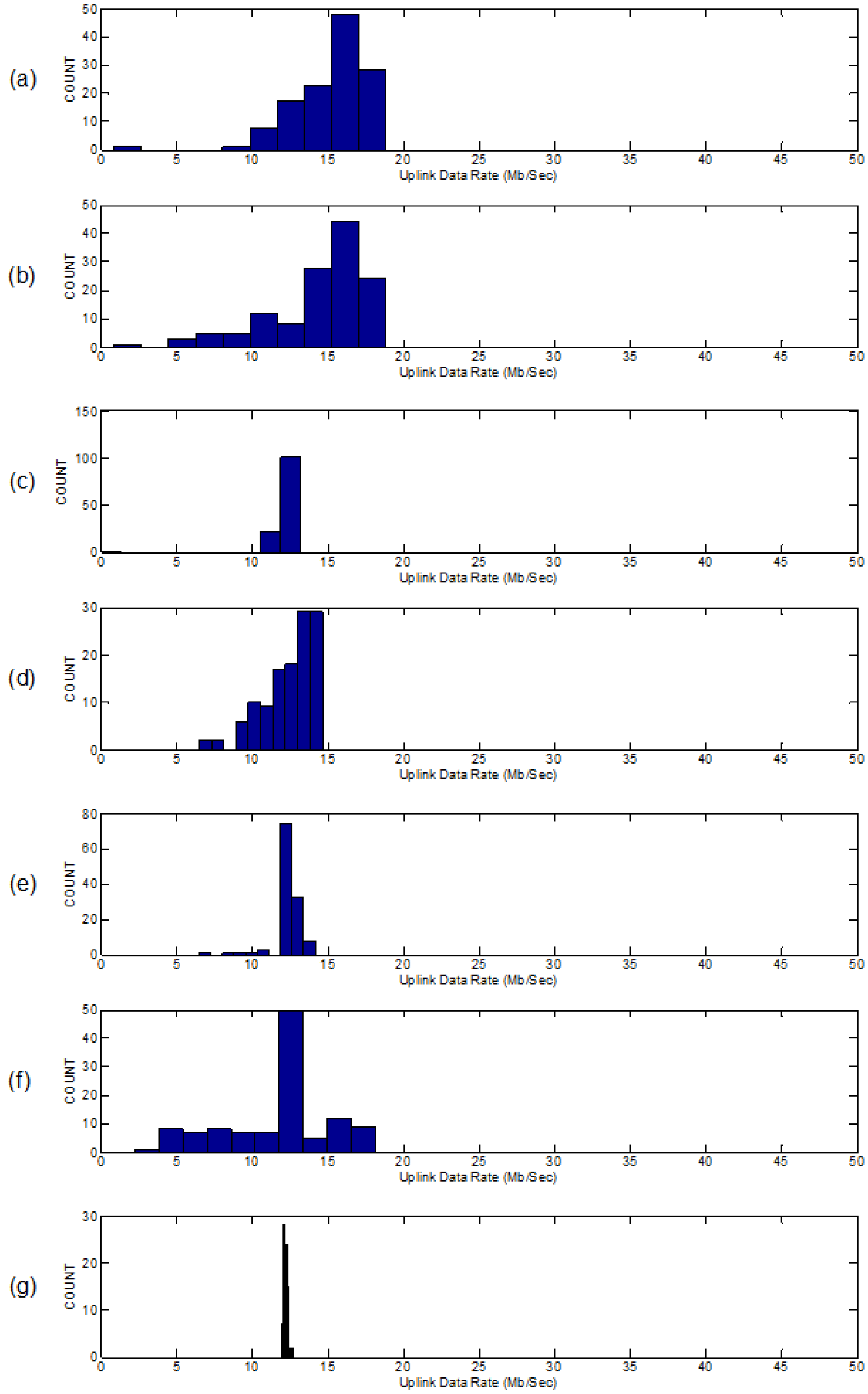

Figure 70. Level 1B histograms of PUSCH for different coverage combinations with a TCP uplink data flow. (a) COW at 8 W, (b) COW at 40 W, (c) small cell at 5 W with discrete antennas, (d) small cell at 5 W with discrete antennas and PSCR MN, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (g) small cell feeding a four-antenna passive DAS system.

Table 25. Level 1B PDSCH statistics for a TCP downlink data flow.

Coverage Combination	Mean PDSCH (Mb/s)	Median PDSCH (Mb/s)	Standard Deviation (Mb/s)	Min PDSCH (Mb/s)	Max PDSCH (Mb/s)
COW 8 W	20.2	23.5	10.6	0.0	36.4
COW 40 W	24.0	28.3	8.7	0.0	35.8
SCDA 5 W	25.1	25.5	3.8	0.0	33.2
SCDA 5 W+ PSCR MN	31.6	32.2	6.3	0.0	51.0
SCDA 5 W + COW 8 W+ PSCR MN	27.5	28.7	9.8	0.0	45.1
SCDA 5 W + COW 40 W + PSCR MN	22.6	22.5	13.8	0.0	48.7
SCDAS	38.6	38.6	7.6	0.0	56.5

Table 26. Level 1B PUSCH statistics for a TCP uplink data flow.

Coverage Combination	Mean PUSCH (Mb/s)	Median PUSCH (Mb/s)	Standard Deviation (Mb/s)	Min PUSCH (Mb/s)	Max PUSCH (Mb/s)
COW 8 W	15.2	15.7	2.5	0.8	18.8
COW 40 W	12.0	15.4	3.3	0.8	18.9
SCDA 5 W	12.4	12.1	1.1	2.5	13.2
SCDA 5 W+ PSCR MN	12.4	12.9	1.7	6.5	14.6
SCDA 5 W + COW 8 W+ PSCR MN	12.4	12.5	0.9	6.5	14.2
SCDA 5 W + COW 40 W + PSCR MN	11.7	12.2	3.5	2.2	18.2
SCDAS	12.2	12.2	0.1	12.0	12.7

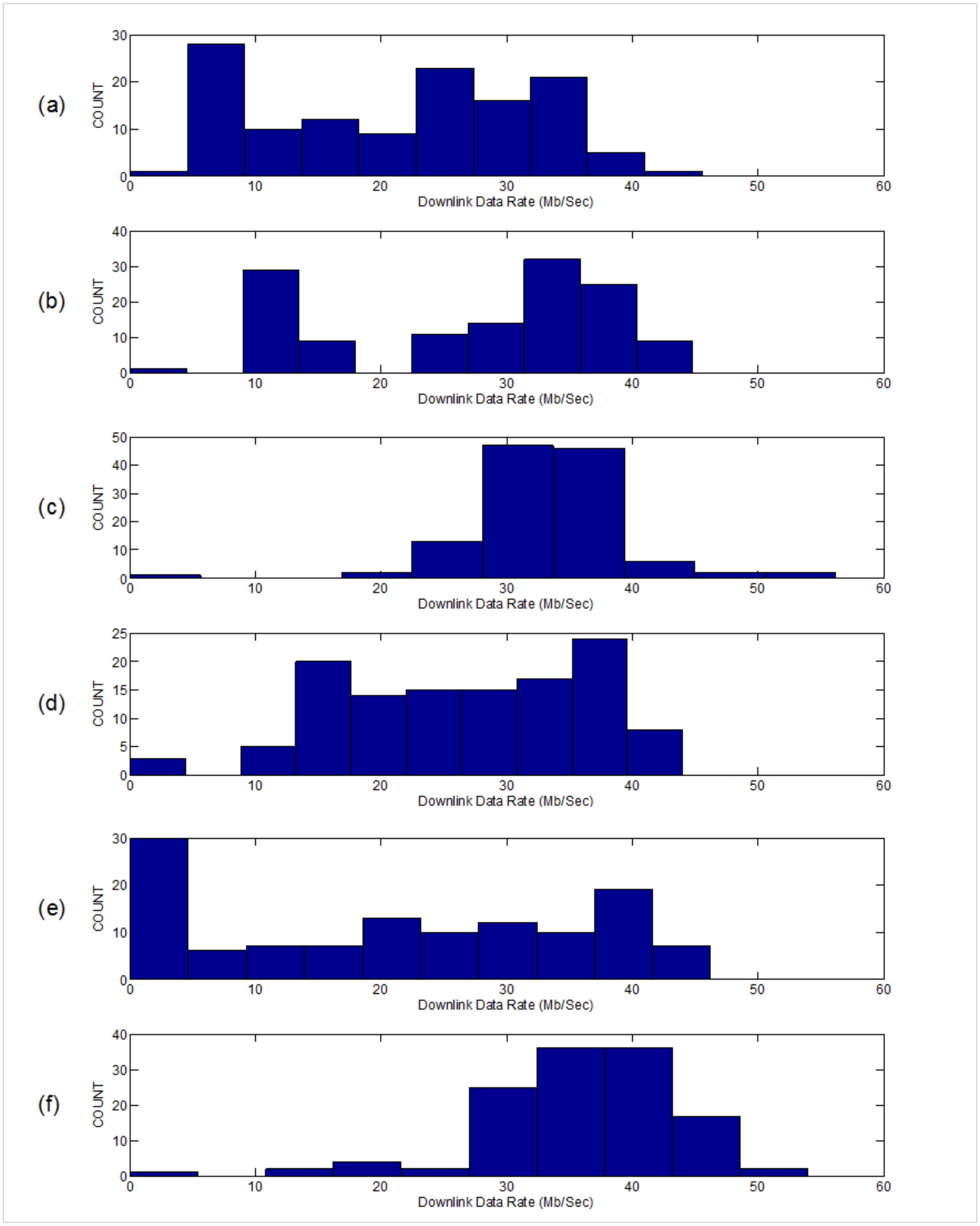

Figure 71. Level 1B histograms of PDSCH for different coverage combinations with a UDP downlink data flow. (a) COW at 8 W, (b) COW at 40 W, (c) small cell at 5 W with discrete antennas and PSCR MN, (d) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (f) small cell feeding a four-antenna passive DAS system.

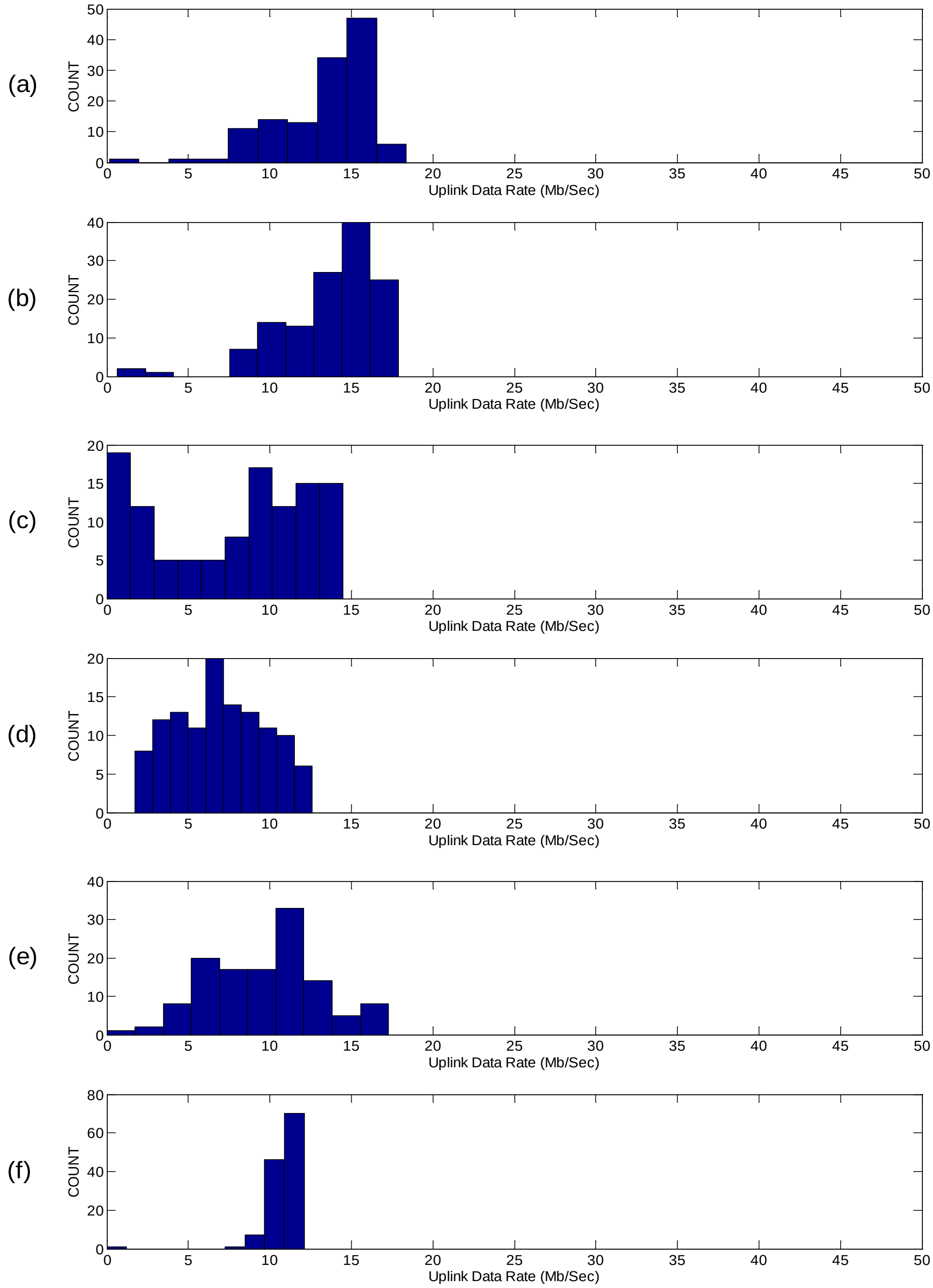

Figure 72. Level 1B histograms of PUSCH for different coverage combinations with a UDP uplink data flow. (a) COW at 8 W, (b) COW at 40 W, (c) small cell at 5 W with discrete antennas and PSCR MN, (d) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (f) small cell feeding a four-antenna passive DAS system.

Table 27. Level 1B PDSCH statistics for a UDP downlink data flow.

Coverage Combination	Mean PDSCH (Mb/s)	Median PDSCH (Mb/s)	Standard Deviation (Mb/s)	Min PDSCH (Mb/s)	Max PDSCH (Mb/s)
COW 8 W	21.2	24.0	10.9	0.0	45.6
COW 40 W	27.3	31.7	11.3	0.0	44.8
SCDA 5 W+ PSCR MN	33.4	33.1	6.1	0.0	56.2
SCDA 5 W + COW 8 W+ PSCR MN	26.8	27.7	9.9	0.0	44.0
SCDA 5 W + COW 40 W + PSCR MN	20.9	21.8	15.4	0.0	46.3
SCDAS	36.4	37.1	7.5	0.0	54.0

Table 28. Level 1B PUSCH statistics for a UDP uplink data flow.

Coverage Combination	Mean PUSCH (Mb/s)	Median PUSCH (Mb/s)	Standard Deviation (Mb/s)	Min PUSCH (Mb/s)	Max PUSCH (Mb/s)
COW 8 W	13.3	14.4	2.9	0.0	18.4
COW 40 W	13.7	14.4	3.1	0.0	17.8
SCDA 5 W+ PSCR MN	7.6	8.9	4.7	0.0	14.5
SCDA 5 W + COW 8 W+ PSCR MN	7.0	6.8	2.7	0.0	12.6
SCDA 5 W + COW 40 W + PSCR MN	9.6	10.3	3.4	0.0	17.3
SCDAS	10.8	11.0	1.2	0.0	12.1

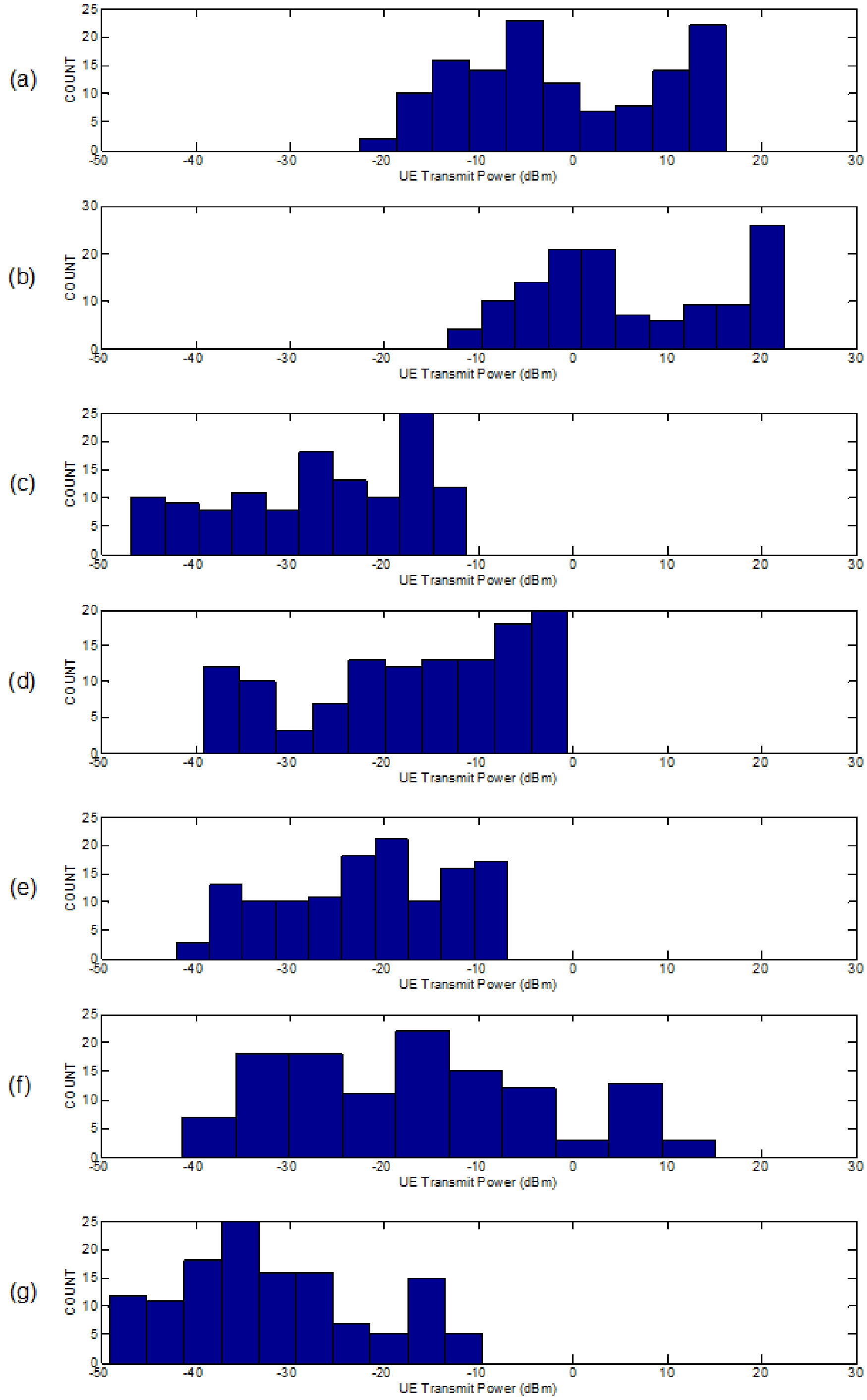

Figure 73. Level 1B histograms of UE transmit power for different coverage combinations with a TCP downlink data flow. (a) COW at 8 W, (b) COW at 40 W, (c) small cell at 5 W with discrete antennas, (d) small cell at 5 W with discrete antennas and PSCR MN, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (g) small cell feeding a four-antenna passive DAS system.

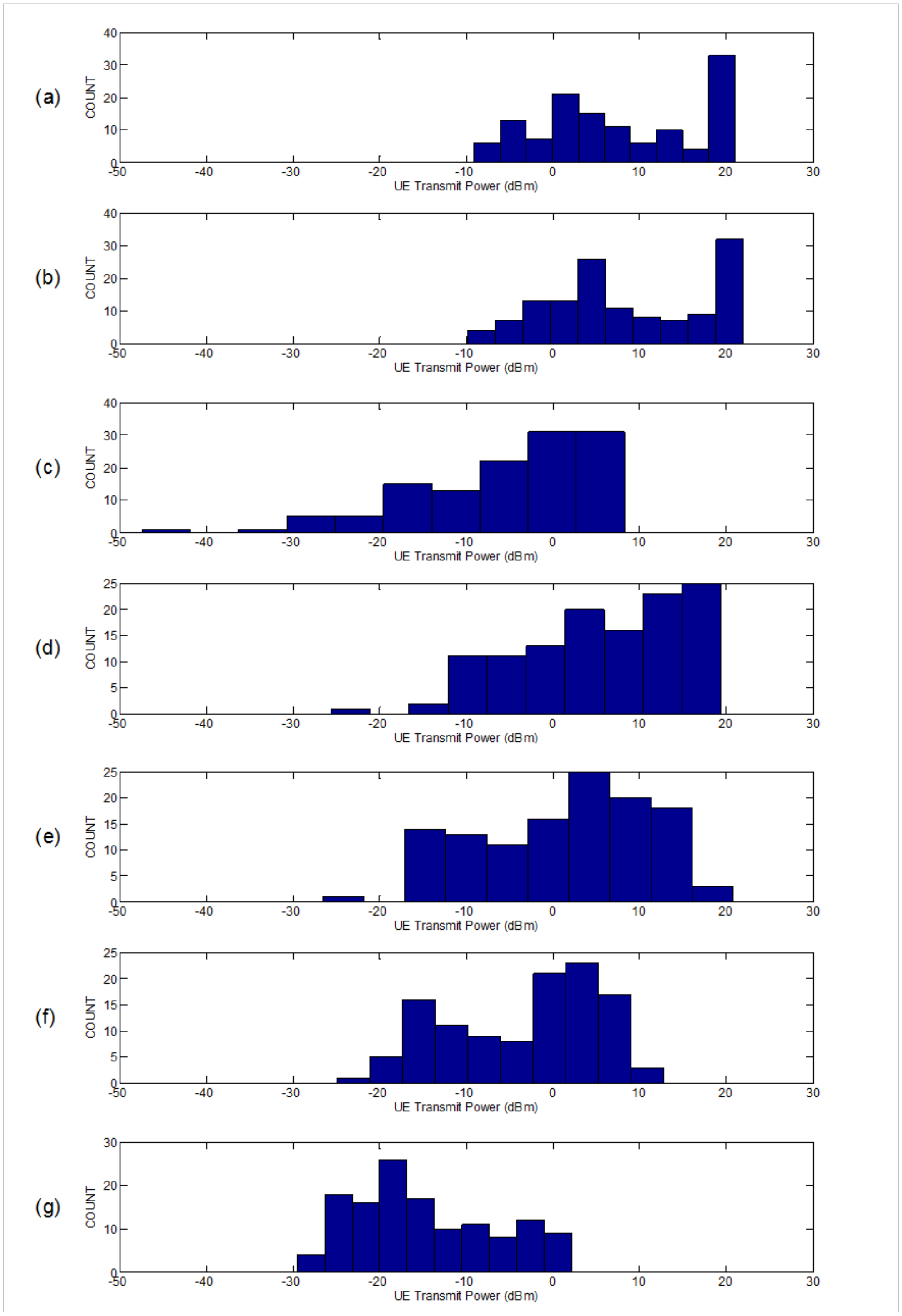

Figure 74. Level 1B histograms of UE transmit power for different coverage combinations with a TCP uplink data flow. (a) COW at 8 W, (b) COW at 40 W, (c) small cell at 5 W with discrete antennas, (d) small cell at 5 W with discrete antennas and PSCR MN, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (g) small cell feeding a four-antenna passive DAS system.

Table 29. Level 1B UE transmit power statistics for a TCP downlink data flow.

Coverage Combination	Mean UEpwr (dBm)	Median UEpwr (dBm)	Standard Deviation (dBm)	Min UEpwr (dBm)	Max UEpwr (dBm)
COW 8 W	-1.2	-3.3	10.7	-22.6	16.2
COW 40 W	6.2	3.6	10.3	-13.3	22.4
SCDA 5 W	-26.8	-25.9	10.0	-46.8	-11.2
SCDA 5 W+ PSCR MN	-16.7	-15.0	11.5	-39.3	-0.6
SCDA 5 W + COW 8 W+ PSCR MN	-22.1	-21.8	9.3	-42.1	-7.0
SCDA 5 W + COW 40 W + PSCR MN	-16.5	-16.1	13.8	-41.4	15.1
SCDAS	-31.7	-33.4	10.2	-49.1	-9.7

Table 30. Level 1B UE transmit power statistics for a TCP uplink data flow.

Coverage Combination	Mean UEpwr (dBm)	Median UEpwr (dBm)	Standard Deviation (dBm)	Min UEpwr (dBm)	Max UEpwr (dBm)
COW 8 W	8.1	6.4	9.4	-9.1	21.0
COW 40 W	8.7	6.4	9.2	-9.8	22.0
SCDA 5 W	-5.3	-2.8	10.6	-47.4	8.3
SCDA 5 W+ PSCR MN	5.7	7.5	9.3	-25.6	19.4
SCDA 5 W + COW 8 W+ PSCR MN	1.2	2.5	9.8	-26.6	20.8
SCDA 5 W + COW 40 W + PSCR MN	-3.2	-1.0	8.9	-24.9	12.8
SCDAS	-14.7	-16.1	8.2	-29.6	2.2

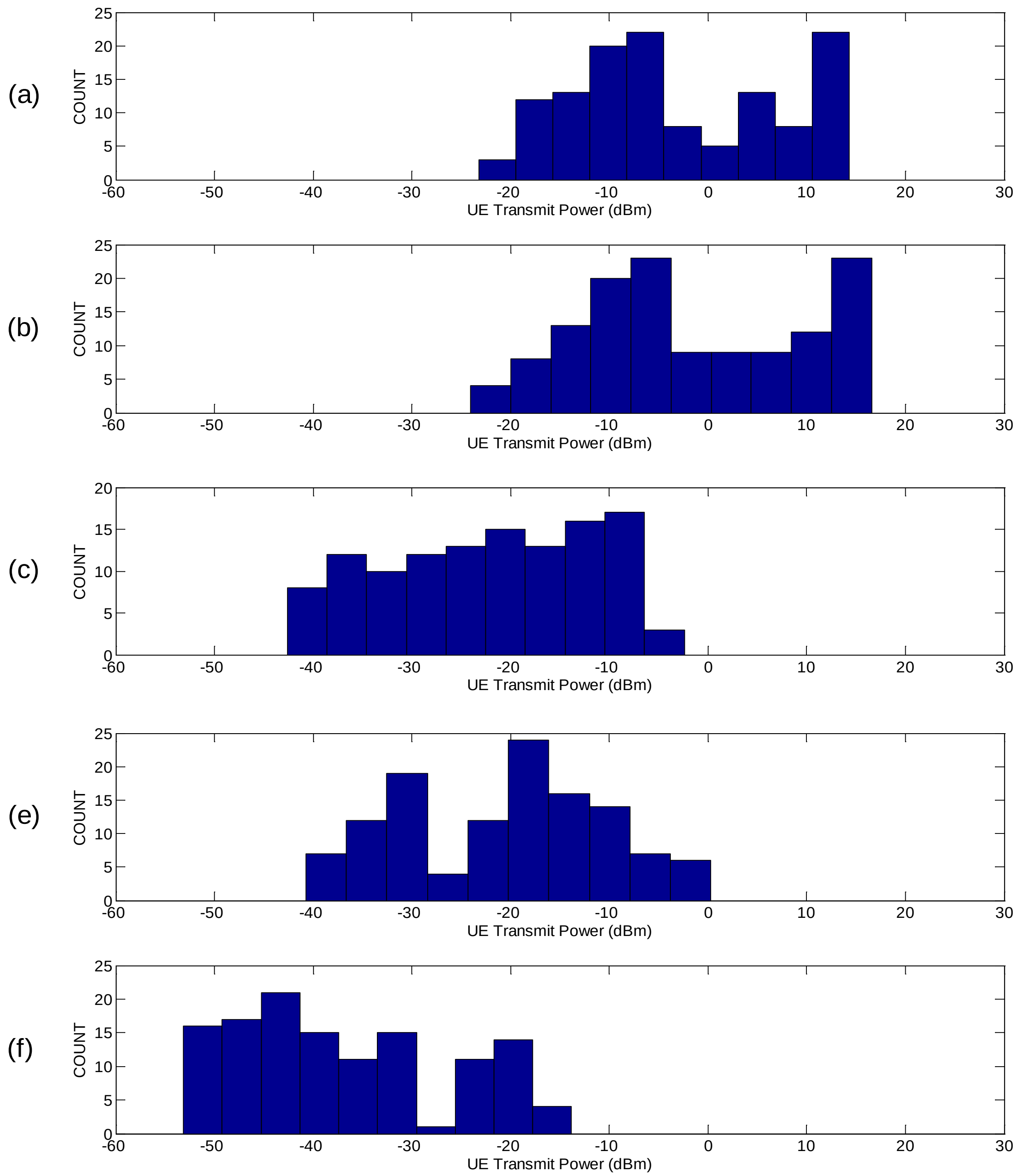

Figure 75. Level 1B histograms of UE transmit power for different coverage combinations with a UDP downlink data flow. (a) COW at 8 W, (b) COW at 40 W, (c) small cell at 5 W with discrete antennas and PSCR MN, (d) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (f) small cell feeding a four-antenna passive DAS system.

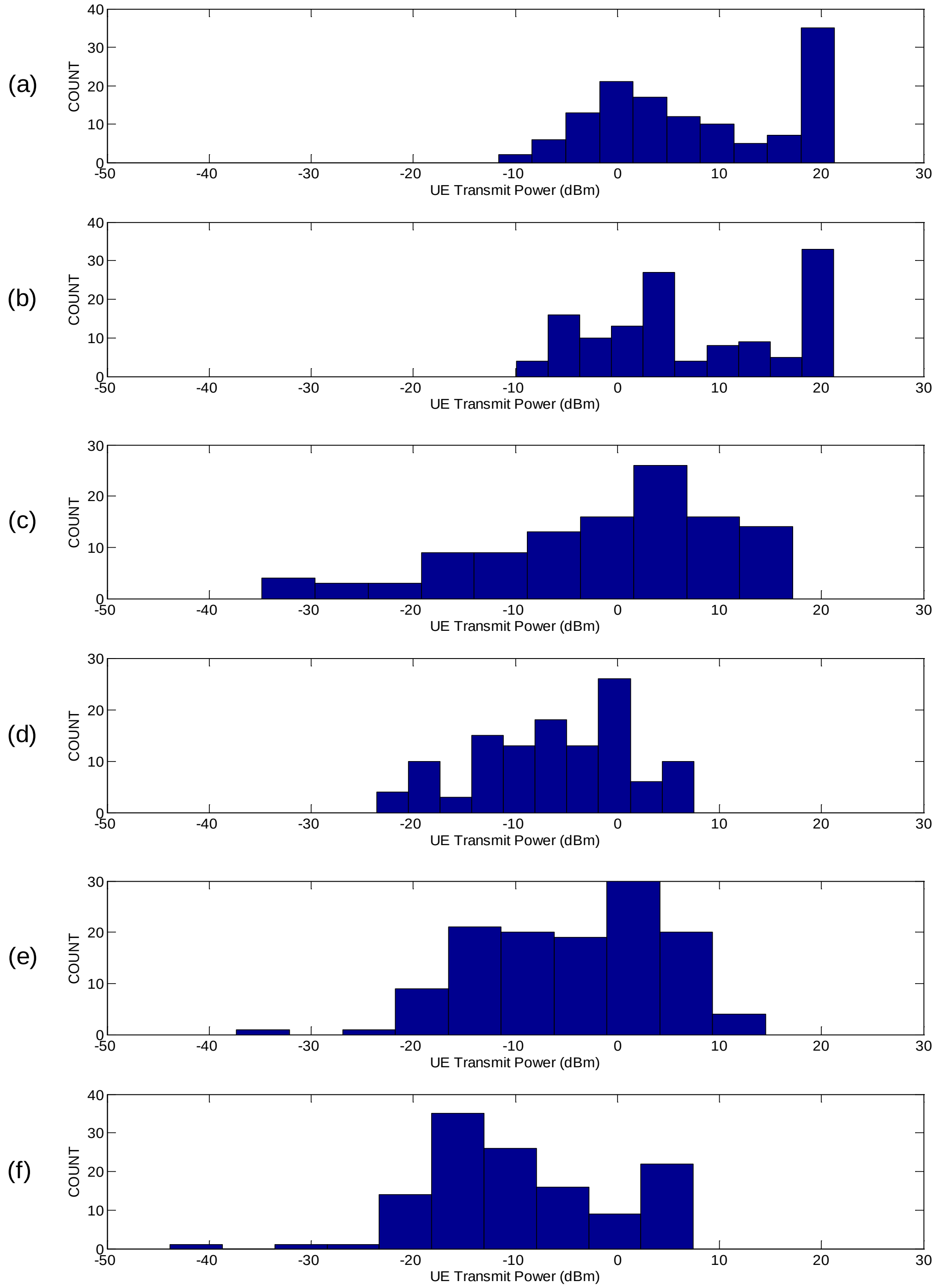

Figure 76. Level 1B histograms of UE transmit power for different coverage combinations with a UDP uplink data flow. (a) COW at 8 W, (b) COW at 40 W, (c) small cell at 5 W with discrete antennas and PSCR MN, (d) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (f) small cell feeding a four-antenna passive DAS system.

Table 31. Level 1B UE transmit power statistics for a UDP downlink data flow.

Coverage Combination	Mean UEpwr (dBm)	Median UEpwr (dBm)	Standard Deviation (dBm)	Min UEpwr (dBm)	Max UEpwr (dBm)
COW 8 W	-3.3	-6.1	10.4	-23.2	14.3
COW 40 W	-1.7	-4.7	10.9	-24.0	16.6
SCDA 5 W+ PSCR MN	-22.0	-20.7	10.5	-42.6	-2.4
SCDA 5 W + COW 8 W+ PSCR MN	-22.5	-23.5	9.6	-42.6	-2.5
SCDA 5 W + COW 40 W + PSCR MN	-20.6	-19.1	10.4	-40.8	0.3
SCDAS	-37.1	-40.0	10.8	-53.1	-13.8

Table 32. Level 1B UE transmit power statistics for a UDP uplink data flow.

Coverage Combination	Mean UEpwr (dBm)	Median UEpwr (dBm)	Standard Deviation (dBm)	Min UEpwr (dBm)	Max UEpwr (dBm)
COW 8 W	7.9	6.1	9.4	-11.6	21.3
COW 40 W	7.6	5.3	9.5	-9.9	21.2
SCDA 5 W+ PSCR MN	-1.7	1.4	12.3	-34.8	17.2
SCDA 5 W + COW 8 W+ PSCR MN	-6.2	-5.4	7.6	-23.6	7.5
SCDA 5 W + COW 40 W + PSCR MN	-4.2	-3.6	8.9	-37.3	14.5
SCDAS	-9.5	-11.2	9.1	-43.8	7.4

3.3 DLC Level 1 Measured Results

Level 1 is the first floor that is completely covered by the PSCR MN. Connectivity is achieved over the entire walk route. We use the same combination of in-building coverage support that was used on level 1B, including the four-antenna SCDAS system installed on level 1B, one floor below. There is strong electromagnetic coupling between the floors via the open foyer on the south end of the DLC, and as the results of this section show, the SCDAS performs quite well. Once again, the SCDAS was not used in combination with either the PSCR MN or the COW, due to tight time constraints. We collected data for both uplink and downlink data flows using both TCP and UDP.

Results were obtained on level 1 for the following eight coverage combinations:

- PSCR MN only
- SCDA only at 5 W input
- COW only at 8 W
- COW only at 40 W
- PSCR MN + SCDA with 5 W input

- PSCR MN + SCDA with 5 W input + COW at 40 W
- PSCR MN + SCDA with 5 W input + COW at 8 W
- Four-antenna SCDAS

Serving-cell RSRP results, superimposed on the level 1 floor plan, are shown in Figures 77–84 for a TCP downlink data flow. The in-building RSRP levels provided by the PSCR MN are shown in Figure 77. While there is coverage over the entire walk route, the measured signal levels are weak: less than −100 dBm. Using the COW at a transmit power level of either 8 W or 40 W improves the situation significantly, particularly on the east side of the DLC, as can be seen in Figures 78 and 79. Figures 80–83 highlight additional coverage improvements that occur when the SCDA is active. The plots indicate that the influence of both the COW and PSCR MN are minimal and that the small cell dominates the interior coverage. Figure 84 shows the RSRP levels with the four-antenna SCDAS system active on level 1B. The resulting signal levels are very similar to those obtained with the other small cell coverage combinations and this indicates strong coupling between the floors. As mentioned earlier, this is probably caused by signals traveling down the hallways and coupling to the adjacent floors via the open foyer on the south end of the DLC. The RSRP histogram plots of Figures 85–88 and the summary statistics in Tables 33–36 clearly illustrate the impact of the progression of in-building coverage for TCP and UDP data flows.

The CINR signal-to-noise histograms for the coverage combinations are provided in Figures 89−92 for TCP and UDP downlink and uplink data flows. The corresponding summary statistics are given in Tables 37–40. Poor results are seen when coverage is provided by the PSCR MN. This is due to the high path losses between the Green Mountain eNB and the DLC. The high path losses are a result of the combination of the 2.5 km distance between the eNB and the DLC and the blockage effects of the Engineering Center, which is adjacent to the DLC. The results improve dramatically when the COW provides RF coverage from the east side of the DLC. The results improve even more when the small cell with discrete antennas is active and RF coverage is provided from within the building interior. When the COW is added to the SCDA, the resulting CINR values have a larger spread, due to neighbor cell interference effects. The best results again occur with the four-antenna SCDAS providing coverage. This is due to robust inter-floor coupling and the fact that there are no other active coverage elements to cause increased interference.

Histograms of the PDSCH downlink data flow are given in Figures 93 and 95 for TCP and UDP, respectively and summary statistics are provided in Tables 41 and 43. When the macro network is the lone source of coverage, the resulting data rates are low, with maximum rates of less than 6 Mb/s. This reduced performance is due to the combination of high path loss and low RF signal levels. The situation improves significantly with the COW, where maximum data rates of more than 35 Mb/s are obtained with TCP and 45 Mb/s with UDP. These high rates occur on the east side of the DLC where the COW is parked. However, reduced data rates are seen on the west side of the DLC due to blockage effects of interior walls. Using the SCDA combination nearly eliminates the occurrence of low data rates, and the overall picture really improves. When SCDA is used in conjunction with the PSCR MN, maximum data rates in excess of 45 Mb/s are seen for both TCP and UDP. The combination of the COW and the small cell/discrete antennas produces increased occurrences of low data rates, which, in turn, are caused by multiple handovers between the small cell and the COW. This could be remedied by optimizing the hysteresis and offset settings of both the COW and the small cell. Once again this demonstrates that improved RF coverage does not necessarily translate into improved network performance—careful optimization is needed. The best overall performance is achieved with the four-antenna system with a maximum data rate of 50 Mb/s.

The TCP and UDP uplink data flow results are summarized in Figures 94 and 96 respectively. The associated statistical results are shown in Tables 42 and 44. Very low data rates are seen with the PSCR MN because of the high path losses between the UE and Green Mountain eNB. The addition of any coverage combination using either the small cell or the COW greatly improves the uplink data rates. The combination of the small cell and the COW does result in increased occurrences of low data rates, which are caused by multiple handovers. The four-antenna DAS system provides the tightest concentration of data rates throughout the walk route.

The UE transmit power results are shown in Figures 97–100 for TCP/UDP downlink and uplink data flows. The statistical results are summarized in Tables 45–48.The most salient results occur when the PSCR MN provides coverage. In this case, the UE is transmitting at its maximum of +23 dBm (200 mW) throughout the tests, regardless of the direction of data flow and protocol. This high transmit power would translate into reduced battery life for a portable device—the amount of reduction would depend on the specific design and architecture of the device. The best performance, in terms of low transmit power levels, is seen with the four-antenna DAS system. This comes as no surprise, since the DAS system minimizes the serving cell path loss between the UE and eNB.

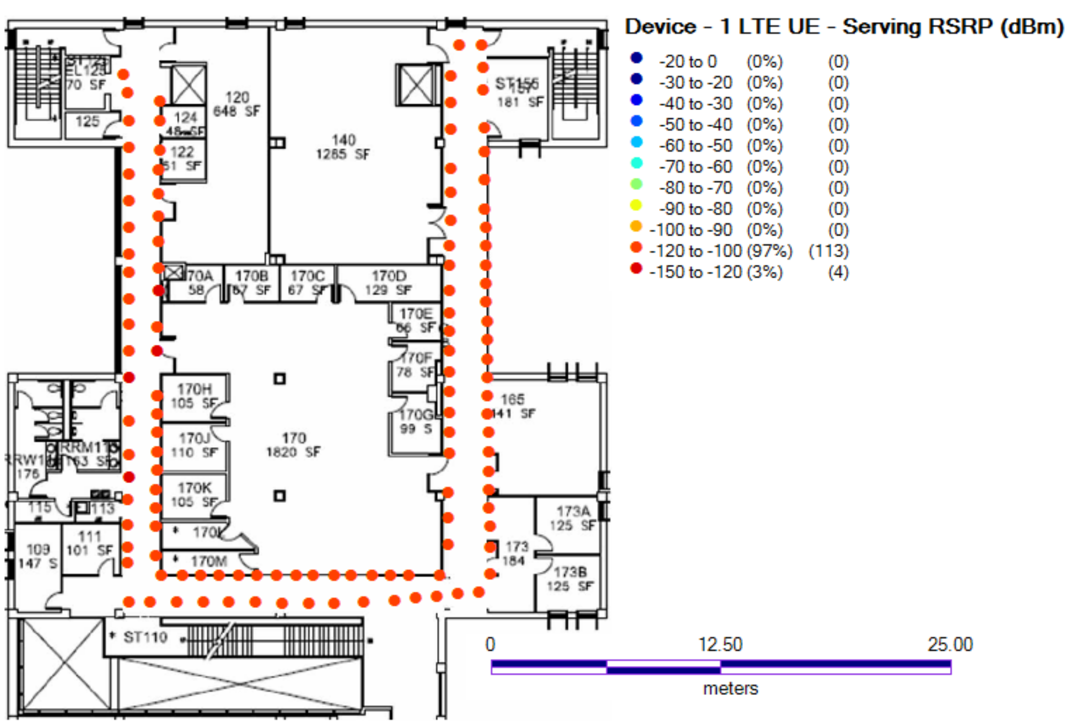

Figure 77. Level 1 reference signal received power (RSRP) for a TCP downlink data flow with the PSCR MN. The direction of top of the floor plan is north.

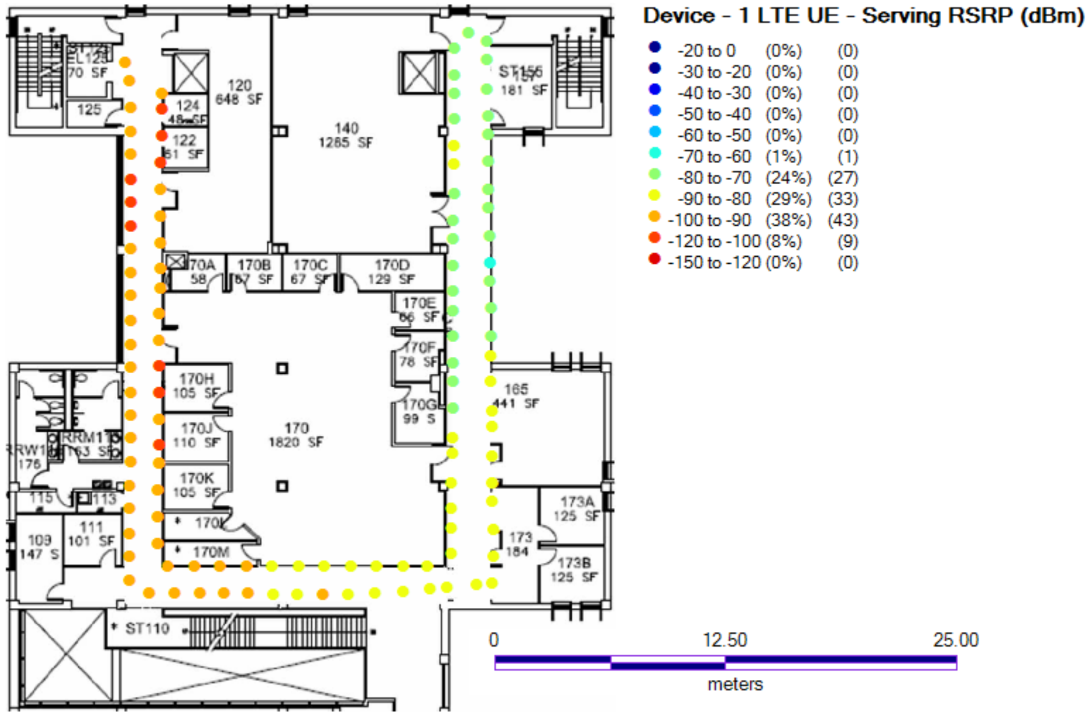

Figure 78. Level 1 reference signal received power (RSRP) with a COW at 8 W for a TCP downlink data flow. The direction of top of the floor plan is north.

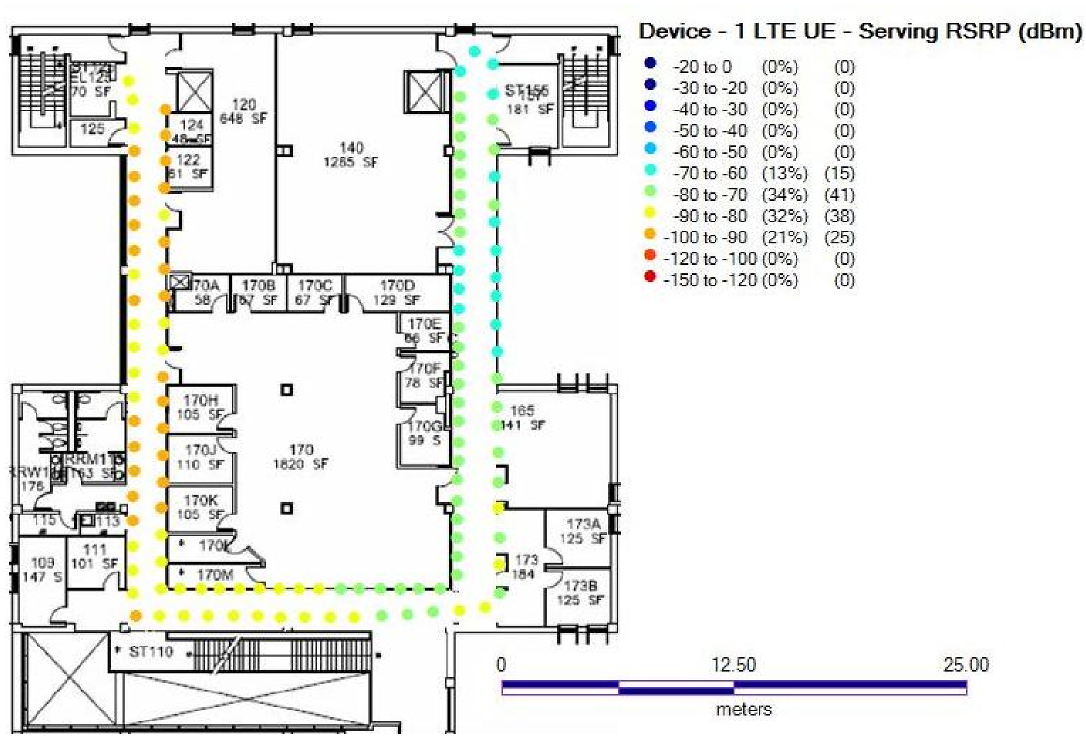

Figure 79. Level 1 reference signal received power (RSRP) for a TCP downlink data flow with a COW at 40 W. The direction of top of the floor plan is north.

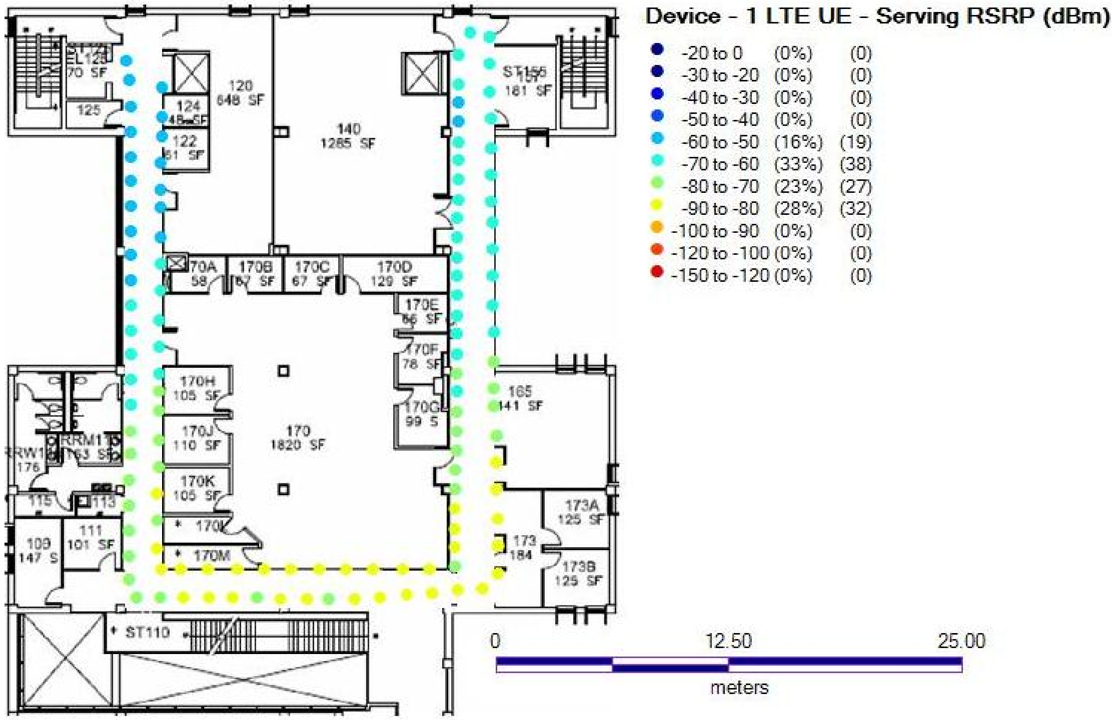

Figure 80. Level 1 reference signal received power (RSRP) for a TCP downlink data flow with a small cell at 5 W and discrete antennas.

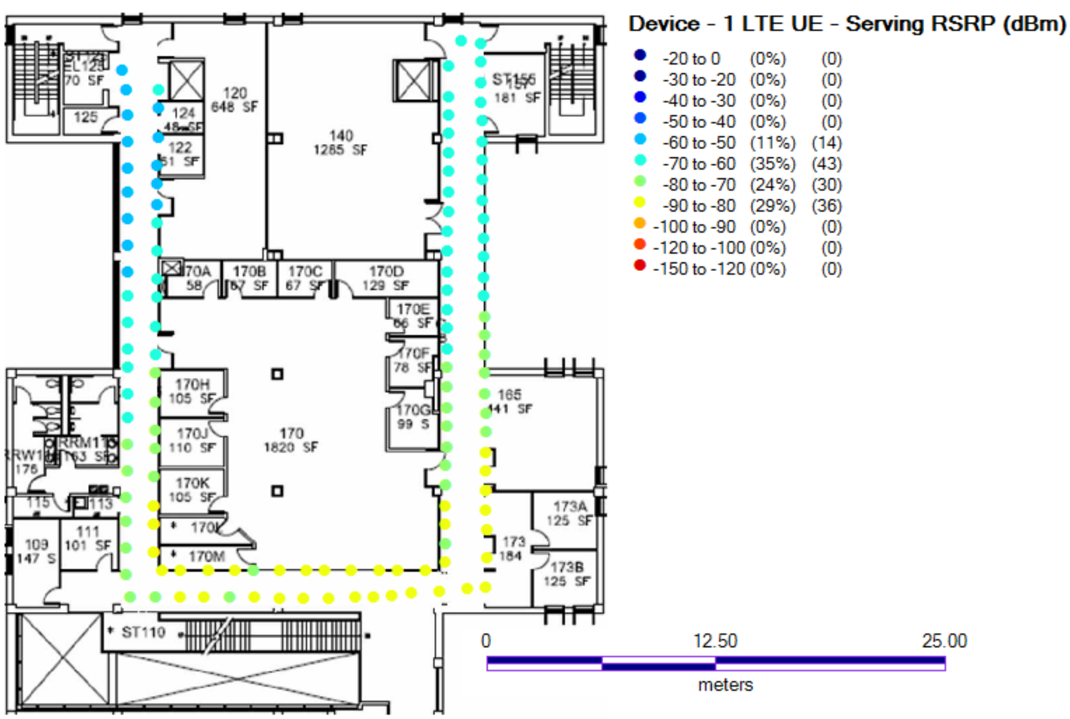

Figure 81. Level 1B reference signal received power (RSRP) for a TCP downlink data flow with a small cell at 5 W and the PSCR MN. The direction of top of the floor plan is north.

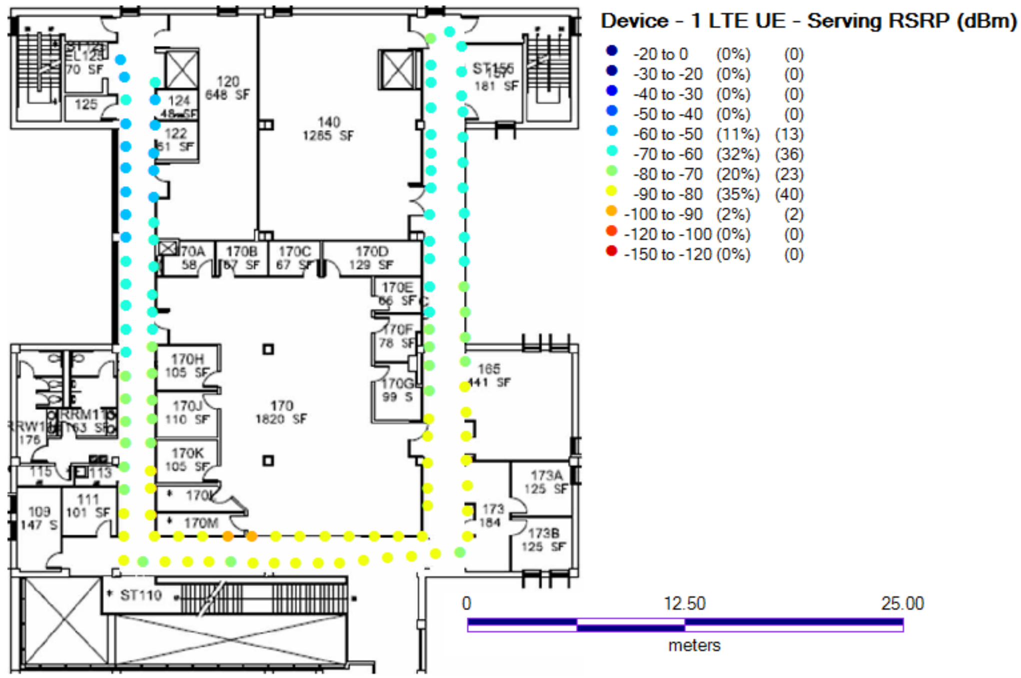

Figure 82. Level 1 reference signal received power (RSRP) for a TCP downlink data flow with a small cell at 5 W, COW at 8 W, and the PSCR MN. The direction of top of the floor plan is north.

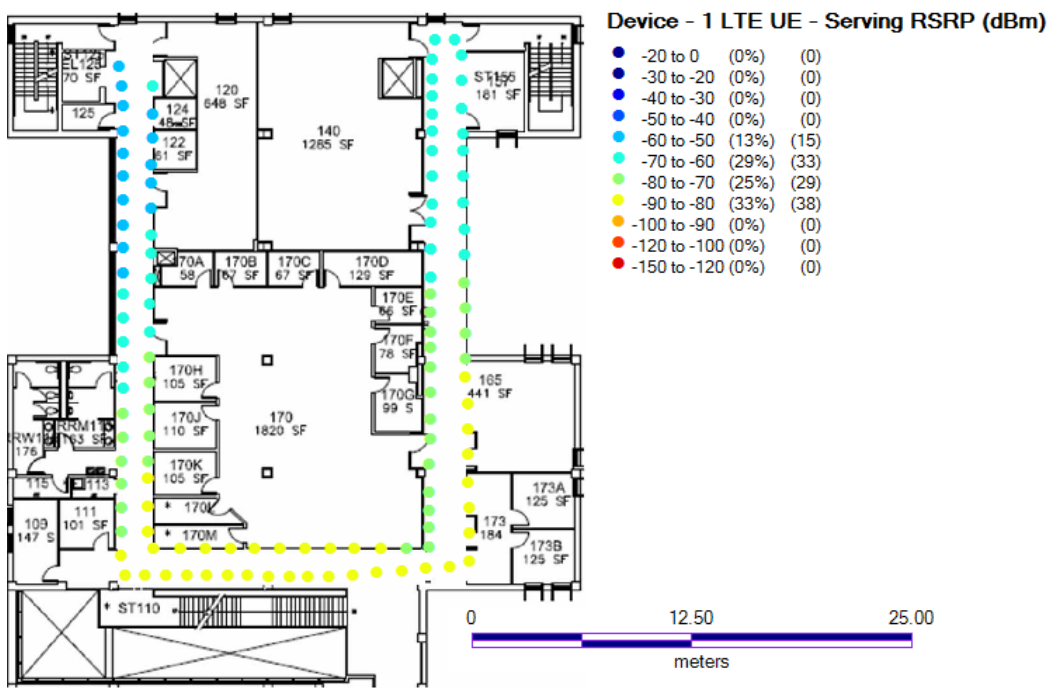

Figure 83. Level 1 reference signal received power (RSRP) for a TCP downlink data flow with a small cell at 5 W, COW at 40 W, and the PSCR MN. The direction of top of the floor plan is north.

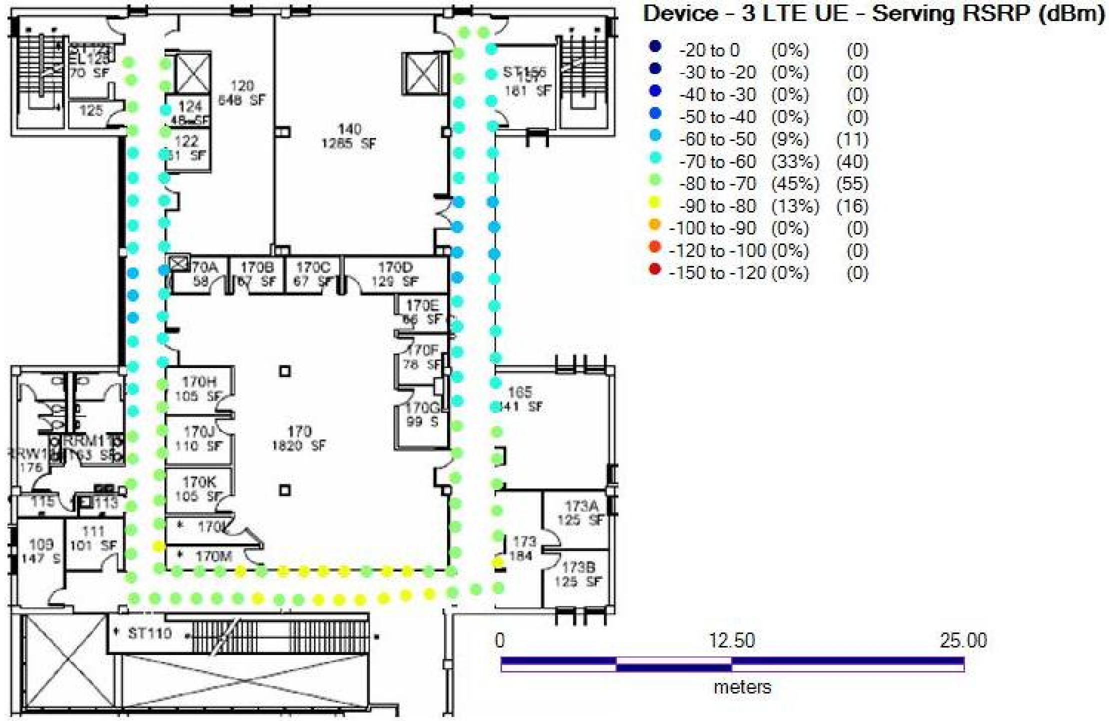

Figure 84. Level 1 reference signal received power (RSRP) for a TCP downlink data flow with a small cell feeding a four-antenna DAS system. The direction of top of the floor plan is north.

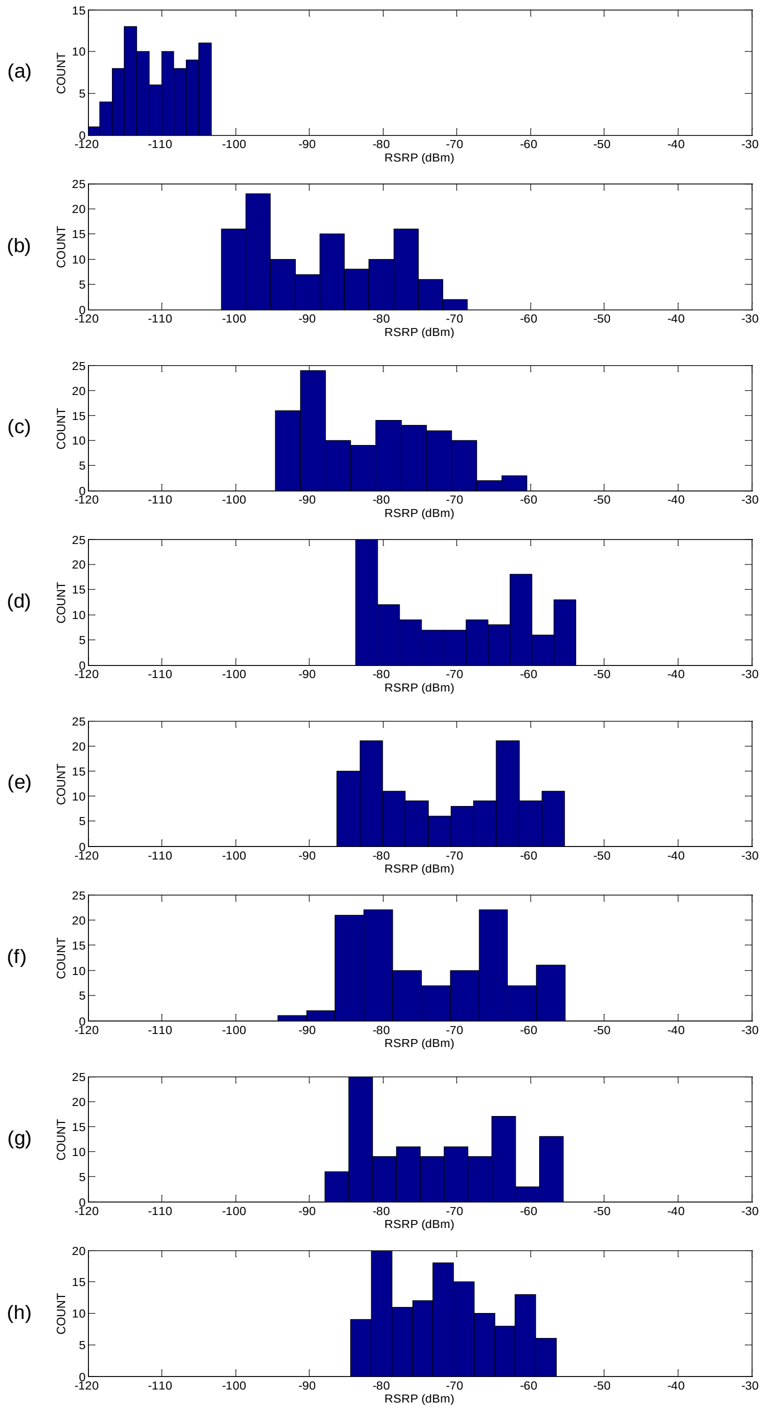

Figure 85. Level 1 histograms of RSRP for different coverage combinations with a TCP downlink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas, (e) small cell at 5 W with discrete antennas and PSCR MN , (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (g) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (h) small cell feeding a four-antenna passive DAS system.

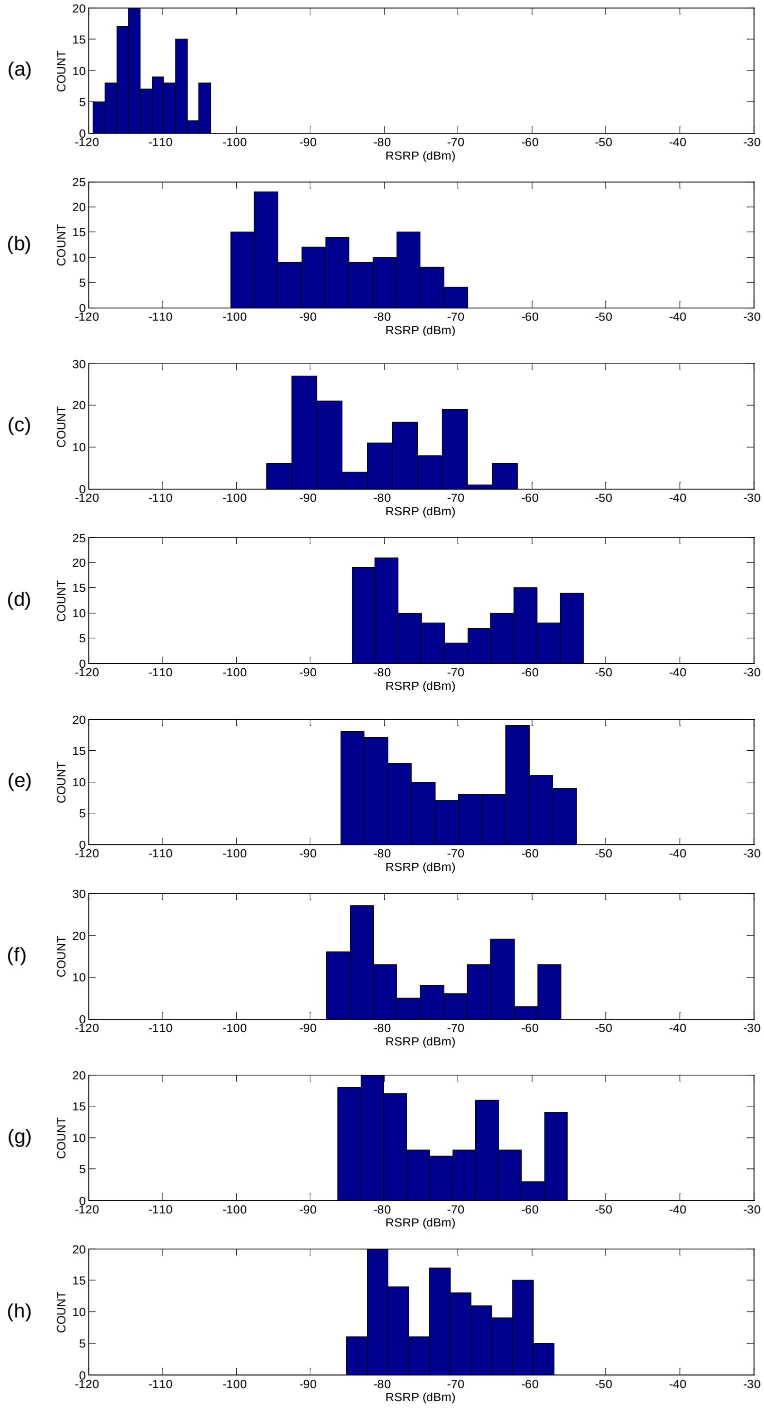

Figure 86. Level 1 histograms of RSRP for different coverage combinations with a TCP uplink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas, (e) small cell at 5 W with discrete antennas and PSCR MN , (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (g) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (h) small cell feeding a four-antenna passive DAS system.

Table 33. Level 1 RSRP statistics for a TCP downlink data flow.

Coverage Combination	**Mean RSRP (dBm)**	**Median RSRP (dBm)**	**Standard Deviation (dBm)**	**Min RSRP (dBm)**	**Max RSRP (dBm)**
PSCR MN	-110.6	-111.2	4.4	-120.0	-103.3
COW 8 W	-88.5	-88.5	9.0	-102	-68.5
COW 40 W	-81.5	-81.3	8.9	-94.6	-60.5
SCDA 5 W	-70.2	-70.8	9.7	-83.7	-53.9
SCDA 5 W+ PSCR MN	-71.9	-72.5	9.6	-86.2	-55.4
SCDA 5 W + COW 8 W+ PSCR MN	-73.3	-74.5	9.6	-94.3	-55.3
SCDA 5 W + COW 40 W + PSCR MN	-72.5	-73.2	9.3	-87.9	-55.6
SCDAS	-71.4	-71.3	7.5	-84.3	-56.5

Table 34. Level RSRP statistics for a TCP uplink data flow.

Coverage Combination	**Mean RSRP (dBm)**	**Median RSRP (dBm)**	**Standard Deviation (dBm)**	**Min RSRP (dBm)**	**Max RSRP (dBm)**
PSCR MN	-111.8	-113.0	4.1	-119.3	-103.5
COW 8 W	-87.3	-87.8	8.9	-100.8	-68.7
COW 40 W	-81.4	-82.1	9.0	-95.9	-61.9
SCDA 5 W	-70.2	-71.5	10.1	-84.4	-53.1
SCDA 5 W+ PSCR MN	-71.3	-71.9	9.8	-85.9	-54.0
SCDA 5 W + COW 8 W+ PSCR MN	-73.7	-74.6	9.9	-87.8	-56.1
SCDA 5 W + COW 40 W + PSCR MN	-73.0	-75.6	9.3	-86.3	-55.2
SCDAS	-71.7	-71.7	7.5	-85.1	-57.0

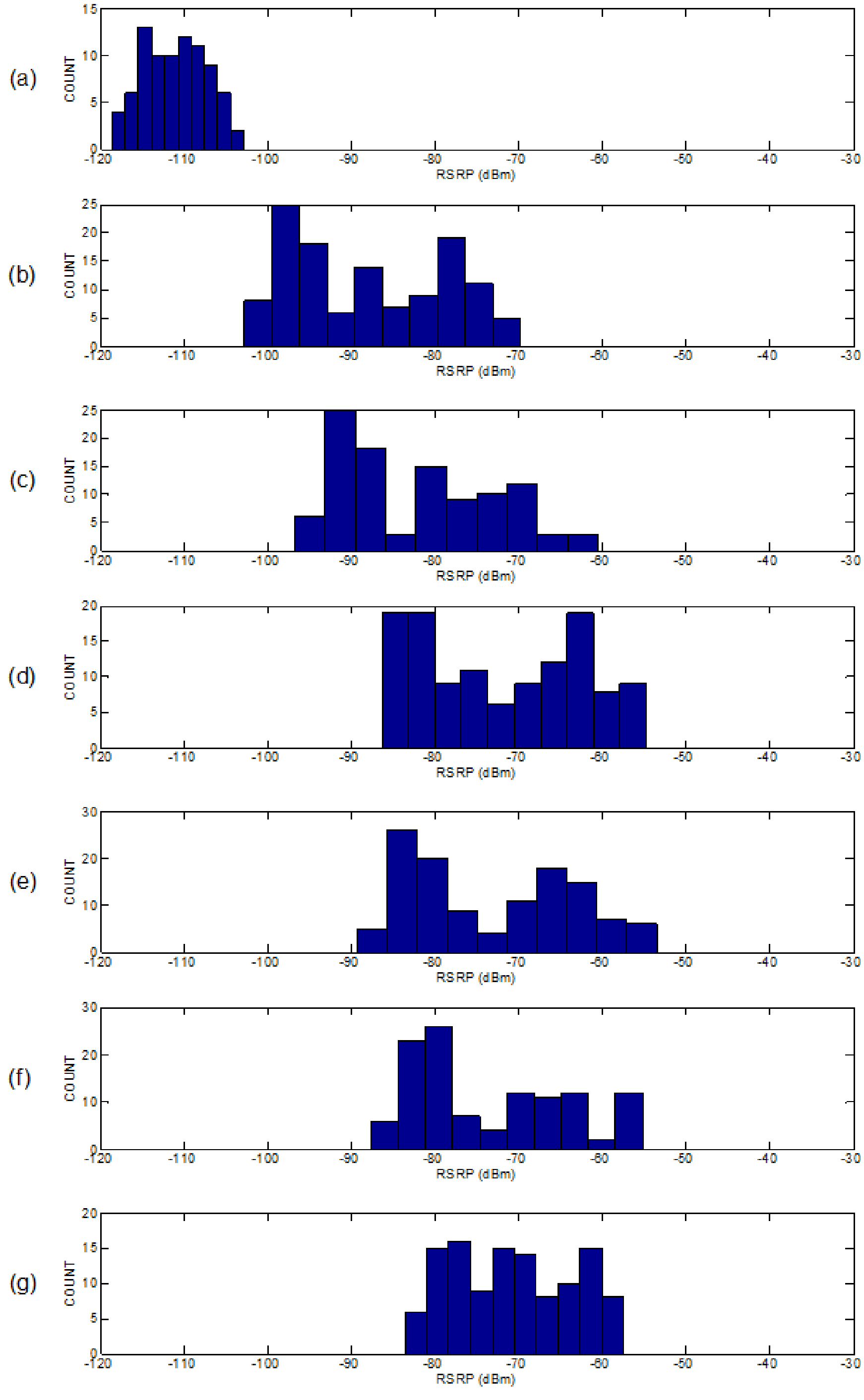

Figure 87. Level 1 histograms of RSRP for different coverage combinations with a UDP downlink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas and PSCR MN, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (g) small cell feeding a four-antenna passive DAS system.

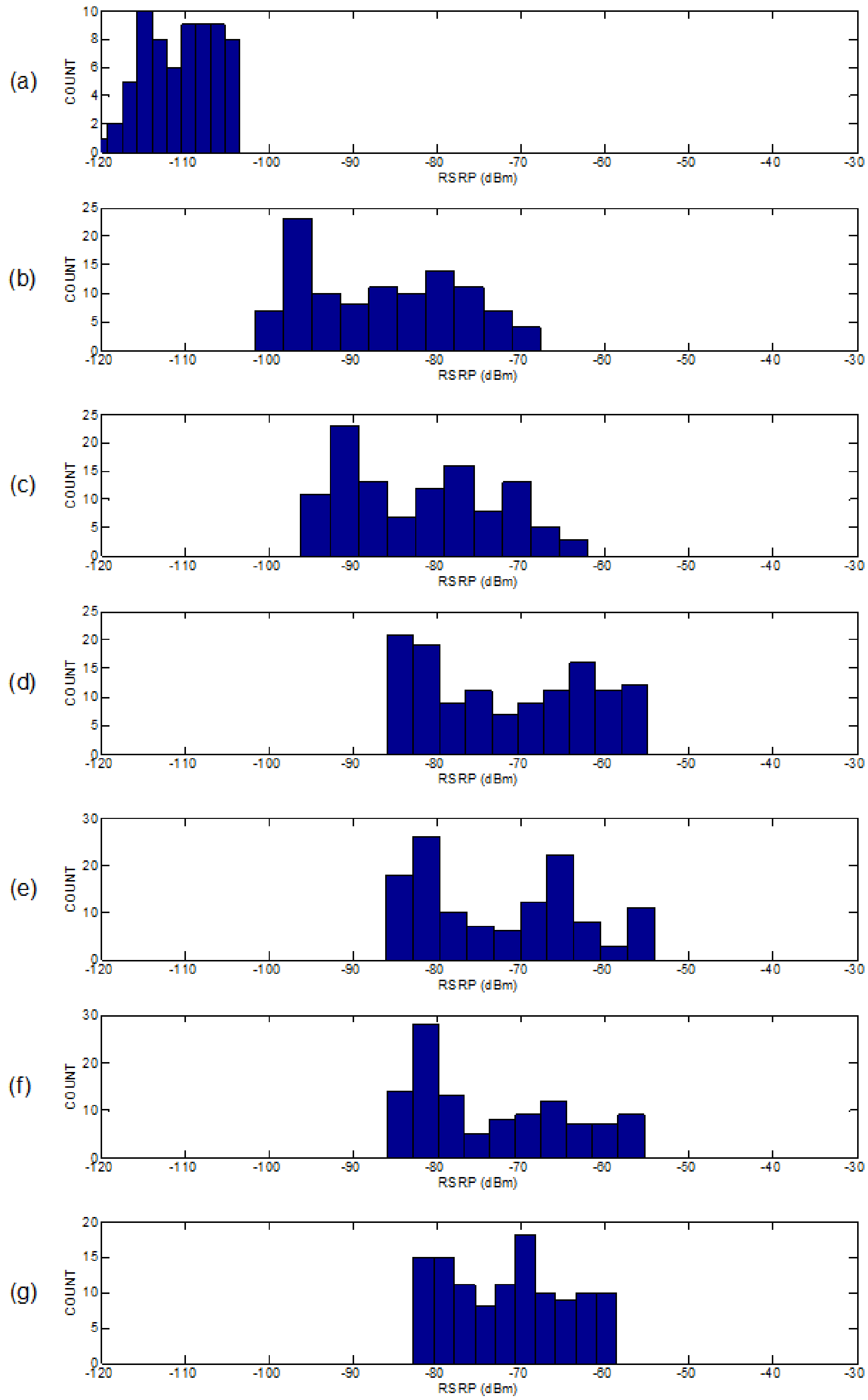

Figure 88. Level 1 histograms of RSRP for different coverage combinations with a UDP uplink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas and PSCR MN, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (g) small cell feeding a four-antenna passive DAS system.

Table 35. Level 1 RSRP statistics for a UDP downlink data flow.

Coverage Combination	Mean RSRP (dBm)	Median RSRP (dBm)	Standard Deviation (dBm)	Min RSRP (dBm)	Max RSRP (dBm)
PSCR MN	-111.4	-111.0	3.8	-118.7	-102.9
COW 8 W	-87.8	-88.5	9.2	-102.8	-69.9
COW 40 W	-82.3	-82.7	9.0	-96.9	-60.5
SCDA 5 W+ PSCR MN	-72.0	-72.5	9.6	-86.4	-54.8
SCDA 5 W + COW 8 W+ PSCR MN	-73.2	-74.9	9.8	-89.3	-53.5
SCDA 5 W + COW 40 W + PSCR MN	-73.5	-77.1	9.2	-87.7	-55.2
SCDAS	-70.8	-70.8	7.2	-83.7	-57.5

Table 36. Level 1 RSRP statistics for a UDP uplink data flow.

Coverage Combination	Mean RSRP (dBm)	Median RSRP (dBm)	Standard Deviation (dBm)	Min RSRP (dBm)	Max RSRP (dBm)
PSCR MN	-110.6	-110.3	4.3	-121.0	-103.6
COW 8 W	-86.7	-86.9	9.1	-101.7	-67.7
COW 40 W	-82.1	-82.0	9.1	-96.2	-62.0
SCDA 5 W+ PSCR MN	-71.7	-71.8	9.8	-86.0	-55.0
SCDA 5 W + COW 8 W+ PSCR MN	-72.5	-73.3	9.4	-86.1	-54.2
SCDA 5 W + COW 40 W + PSCR MN	-73.3	-76.2	9.0	-86.0	-55.4
SCDAS	-71.5	-71.1	7.1	-82.9	-58.7

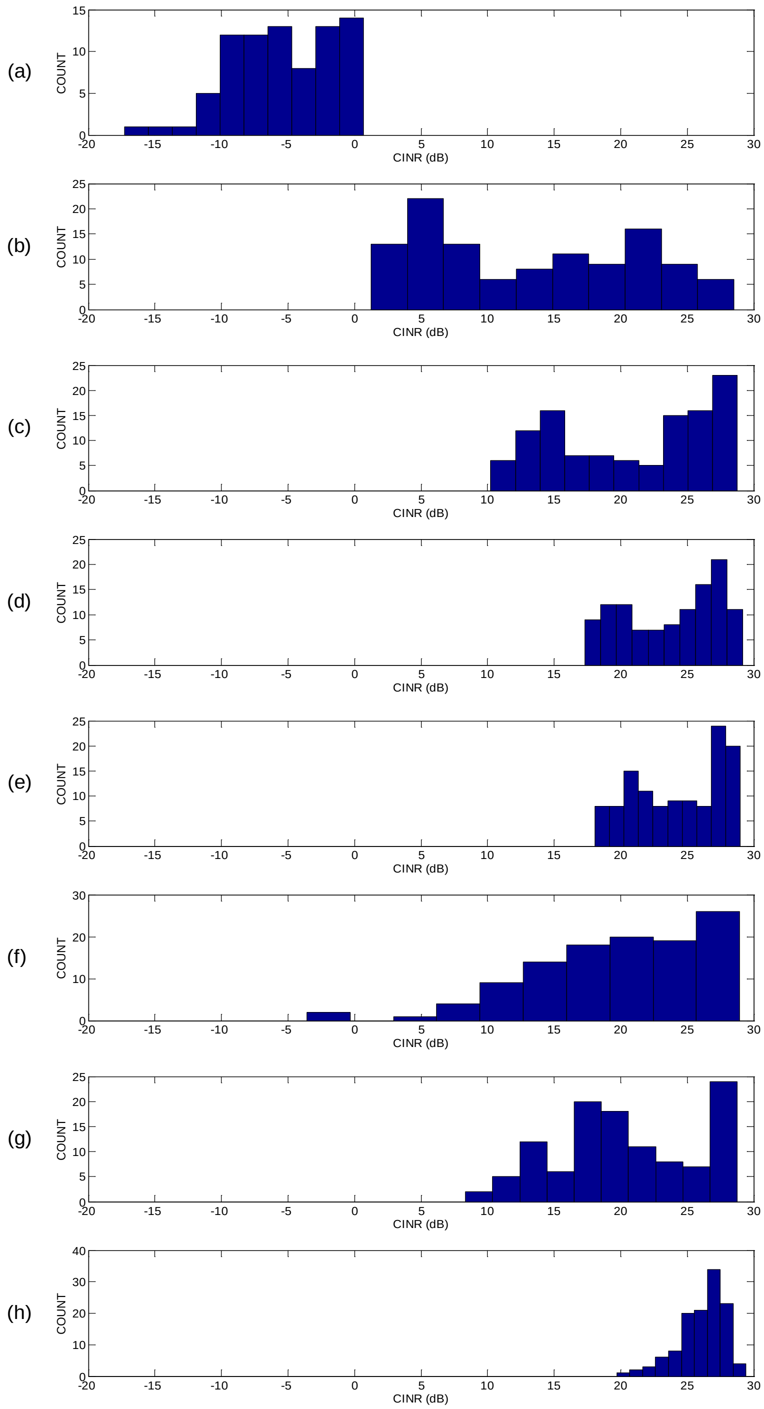

Figure 89. Level 1 histograms of CINR for different coverage combinations with a TCP downlink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas, (e) small cell at 5 W with discrete antennas and PSCR MN , (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (g) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (h) small cell feeding a four-antenna passive DAS system.

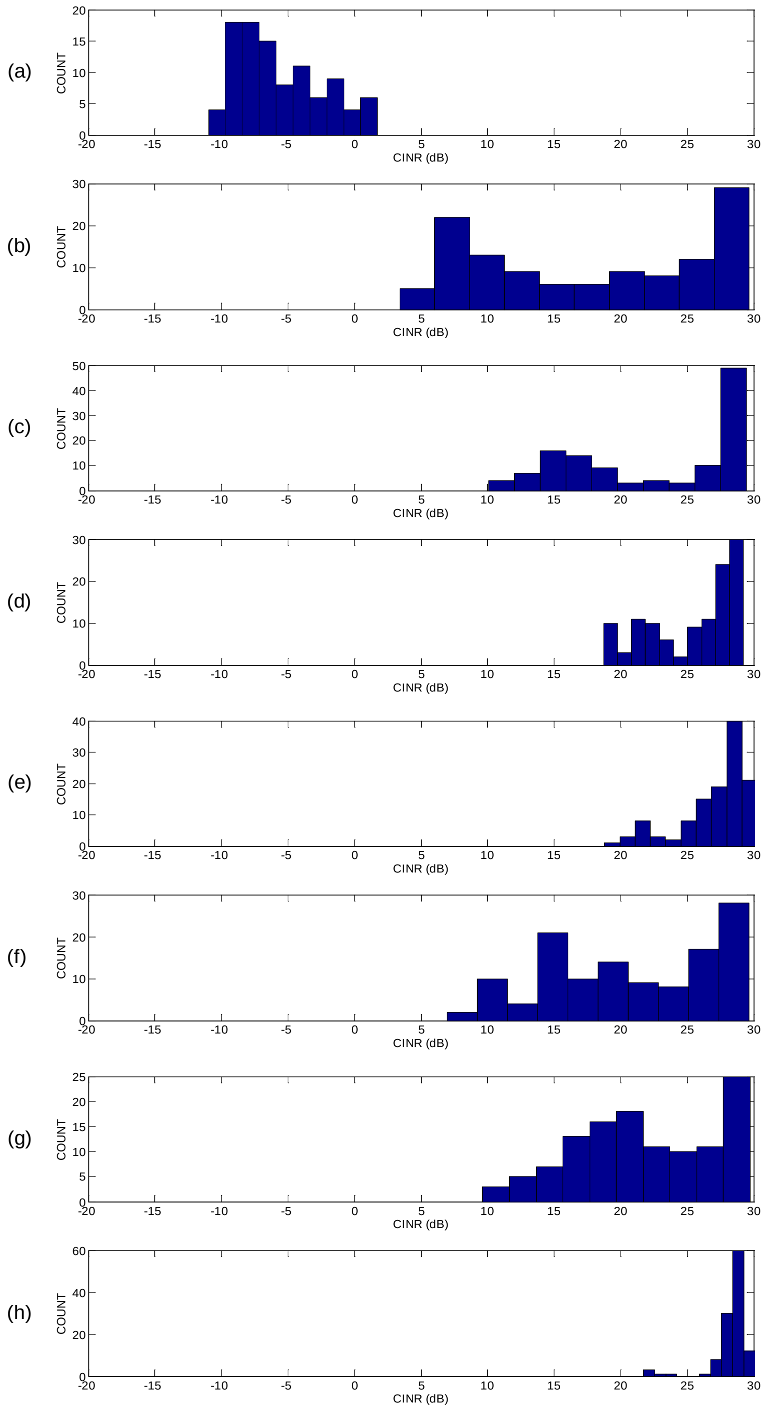

Figure 90. Level 1 histograms of CINR for different coverage combinations with a TCP uplink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas, (e) small cell at 5 W with discrete antennas and PSCR MN , (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (g) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (h) small cell feeding a four-antenna passive DAS system.

Table 37. Level 1 CINR statistics for a TCP downlink data flow.

Coverage Combination	**Mean CINR (dB)**	**Median CINR (dB)**	**Standard Deviation (dB)**	**Min CINR (dB)**	**Max CINR (dB)**
PSCR MN	-5.4	-5.5	3.9	-17.3	0.7
COW 8 W	13.3	13.9	8.1	1.2	28.5
COW 40 W	20.9	22.0	5.7	10.2	28.8
SCDA 5 W	23.8	24.6	3.5	17.3	29.2
SCDA 5 W+ PSCR MN	24.4	24.9	3.3	18.0	29.0
SCDA 5 W + COW 8 W+ PSCR MN	19.7	20.3	6.7	-3.6	29.0
SCDA 5 W + COW 40 W + PSCR MN	20.3	19.5	5.2	8.3	28.8
SCDAS	26.1	26.5	1.7	19.7	29.4

Table 38. Level 1 CINR statistics for a TCP uplink data flow.

Coverage Combination	**Mean CINR (dB)**	**Median CINR (dB)**	**Standard Deviation (dB)**	**Min CINR (dB)**	**Max CINR (dB)**
PSCR MN	-5.6	-6.3	3.2	-11.0	1.7
COW 8 W	17.9	18.7	8.5	3.4	29.6
COW 40 W	22.5	25.5	6.3	10.1	29.5
SCDA 5 W	25.4	26.9	3.3	18.7	29.2
SCDA 5 W+ PSCR MN	27.1	28.1	2.6	18.8	30.3
SCDA 5 W + COW 8 W+ PSCR MN	20.9	21.0	6.4	7.0	29.7
SCDA 5 W + COW 40 W + PSCR MN	21.8	21.1	5.3	9.6	29.7
SCDAS	28.3	28.6	1.4	21.7	30.1

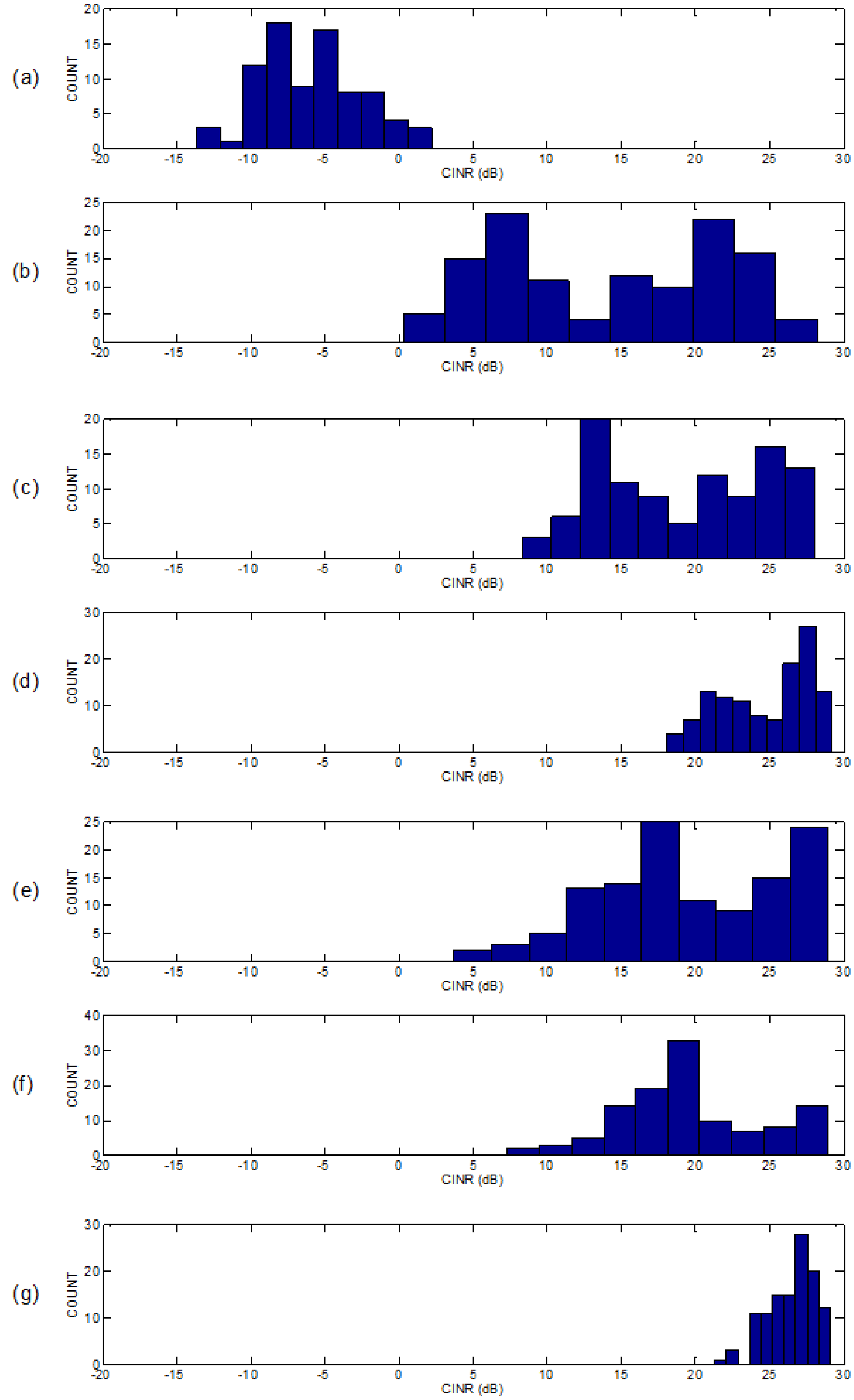

Figure 91. Level 1 histograms of CINR for different coverage combinations with a UDP downlink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas and PSCR MN, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (g) small cell feeding a four-antenna passive DAS system.

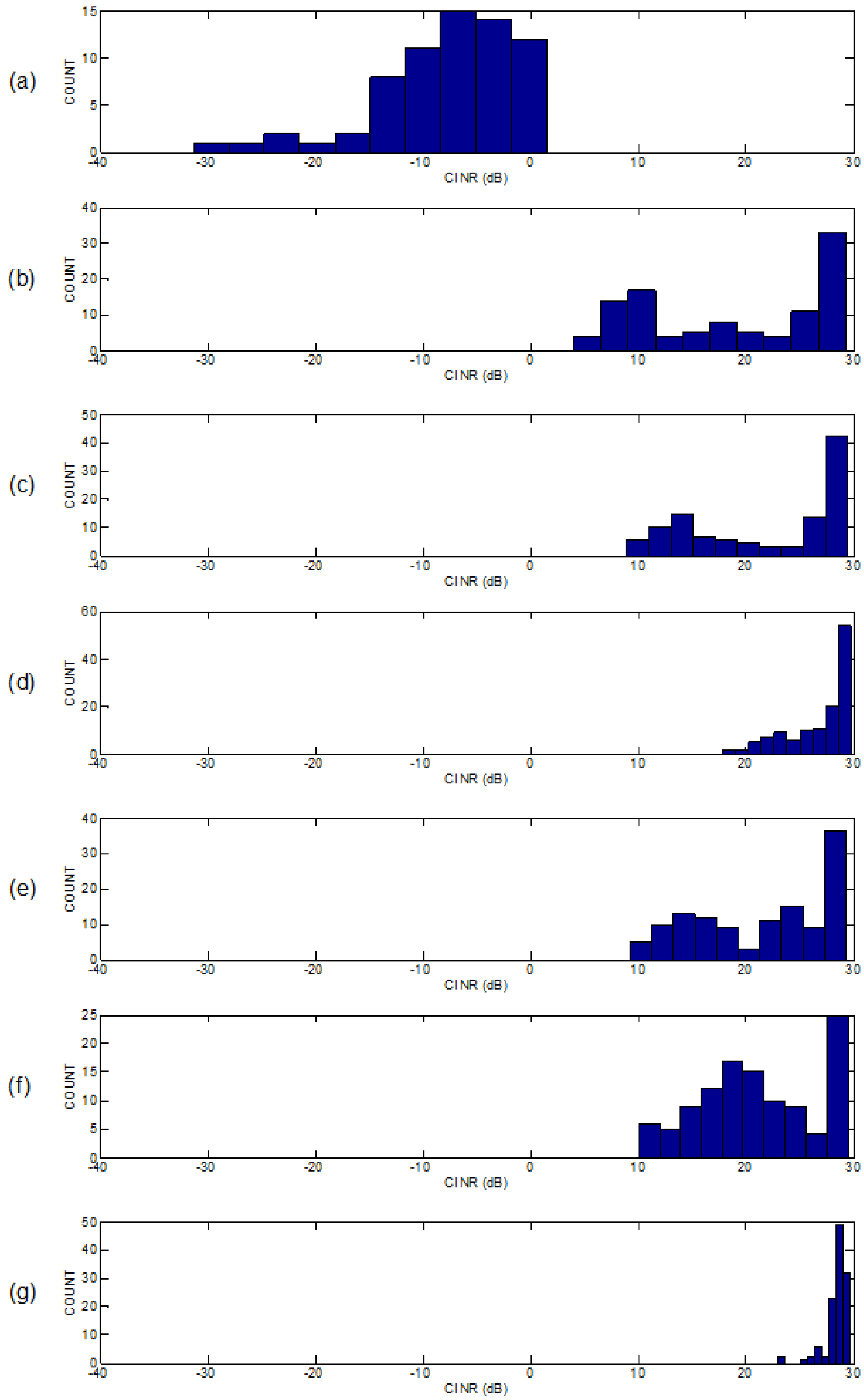

Figure 92. Level 1 histograms of CINR for different coverage combinations with a UDP uplink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas and PSCR MN ,(e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (g) small cell feeding a four-antenna passive DAS system.

Table 39. Level 1 CINR statistics for a UDP downlink data flow.

Coverage Combination	**Mean CINR (dB)**	**Median CINR (dB)**	**Standard Deviation (dB)**	**Min CINR (dB)**	**Max CINR (dB)**
PSCR MN	-6.0	-6.1	3.4	-13.7	2.2
COW 8 W	14.2	15.0	7.8	0.3	28.2
COW 40 W	19.1	19.9	5.6	8.3	28.0
SCDA 5 W+ PSCR MN	24.7	25.6	3.1	18.1	29.2
SCDA 5 W + COW 8 W+ PSCR MN	19.6	18.7	6.1	3.7	29.0
SCDA 5 W + COW 40 W + PSCR MN	19.7	19.2	4.9	7.3	29.0
SCDAS	26.5	26.8	1.6	21.3	29.1

Table 40. Level 1 CINR statistics for a UDP uplink data flow.

Coverage Combination	**Mean CINR (dB)**	**Median CINR (dB)**	**Standard Deviation (dB)**	**Min CINR (dB)**	**Max CINR (dB)**
PSCR MN	-7.7	-6.5	6.6	-31.4	1.5
COW 8 W	18.9	19.2	8.5	4.0	29.3
COW 40 W	21.9	25.3	6.8	9.0	29.4
SCDA 5 W+ PSCR MN	26.7	28.11	2.9	17.9	29.8
SCDA 5 W + COW 8 W+ PSCR MN	21.4	22.7	6.2	9.2	29.3
SCDA 5 W + COW 40 W + PSCR MN	21.1	20.9	5.4	10.0	29.5
SCDAS	28.4	28.6	1.0	23.0	29.7

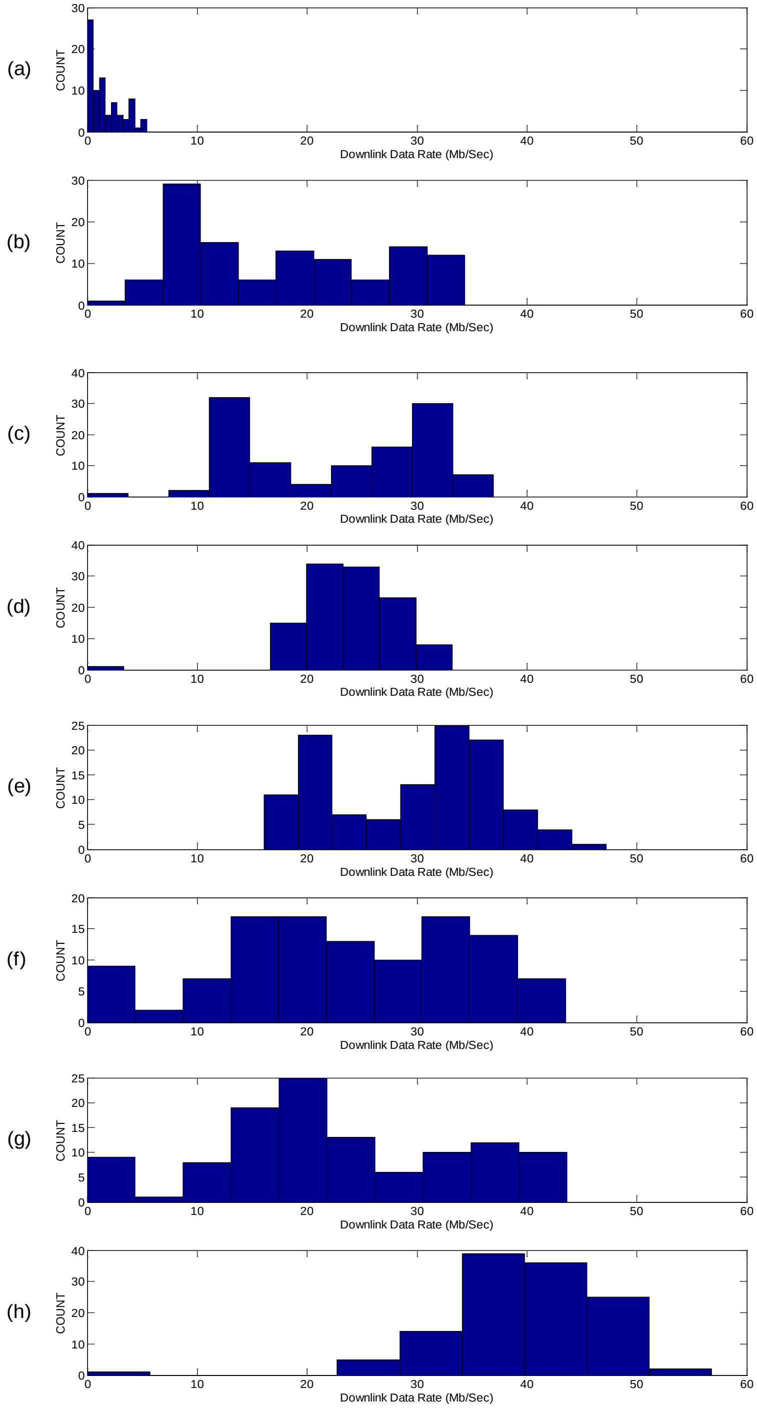

Figure 93. Level 1 histograms of PDSCH for different coverage combinations with a TCP downlink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas, (e) small cell at 5 W with discrete antennas and PSCR MN , (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (g) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (h) small cell feeding a four-antenna passive DAS system.

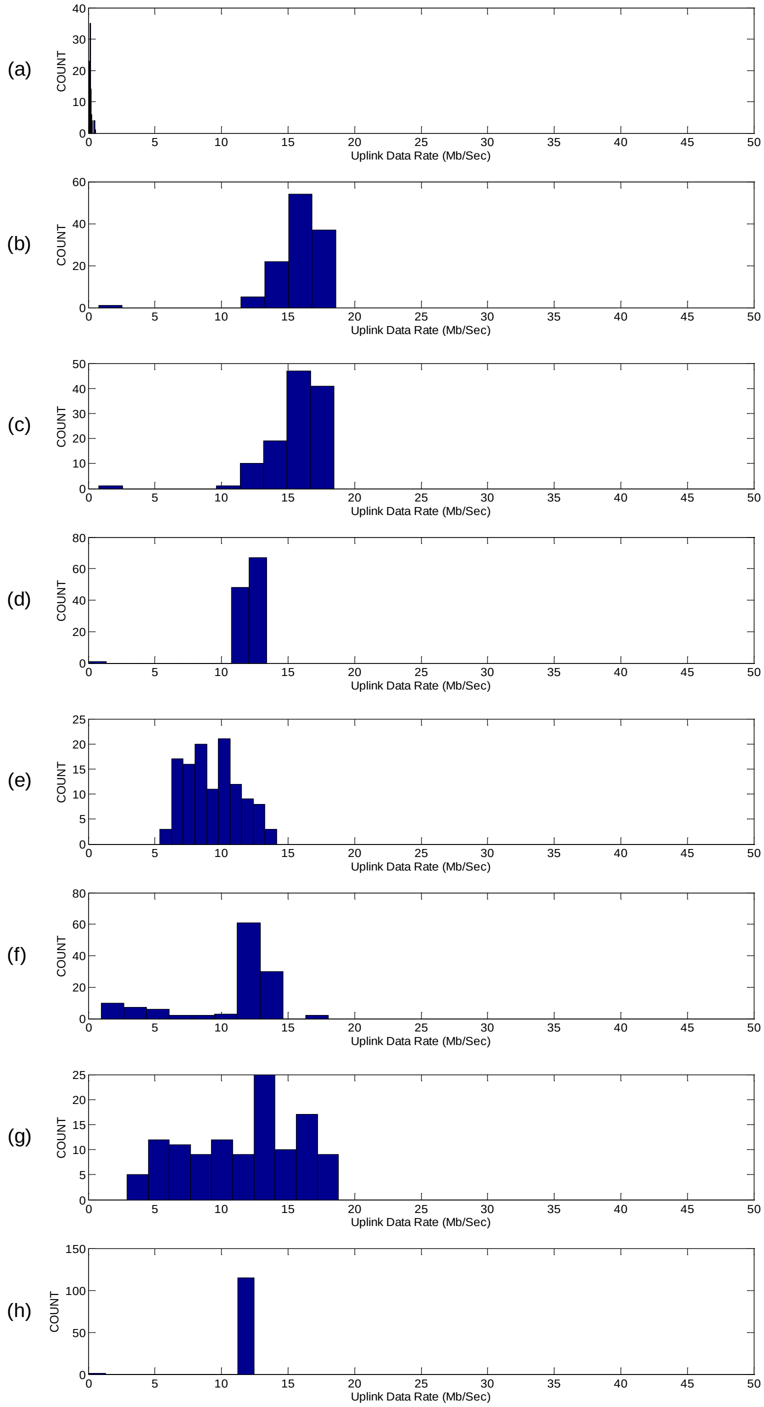

Figure 94. Level 1 histograms of PUSCH for different coverage combinations with a TCP uplink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas, (e) small cell at 5 W with discrete antennas and PSCR MN , (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (g) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (h) small cell feeding a four-antenna passive DAS system.

Table 41. Level 1 PDSCH statistics for a TCP downlink data flow.

Coverage Combination	Mean PDSCH (Mb/s)	Median PDSCH (Mb/s)	Standard Deviation (Mb/s)	Min PDSCH (Mb/s)	Max PDSCH (Mb/s)
PSCR MN	1.6	1.3	1.6	0.0	5.4
COW 8 W	17.8	16.7	9.0	0.0	34.3
COW 40 W	22.8	25.4	8.5	0.0	37.0
SCDA 5 W	24.2	24.2	4.2	0.0	33.2
SCDA 5 W+ PSCR MN	29.6	31.6	7.6	16.1	47.2
SCDA 5 W + COW 8 W+ PSCR MN	23.5	22.9	11.3	0.0	43.5
SCDA 5 W + COW 40 W + PSCR MN	22.5	21.0	11.2	0.0	43.6
SCDAS	40.1	39.9	7.0	0.0	56.8

Table 42. Level 1 PUSCH statistics for a TCP uplink data flow.

Coverage Combination	Mean PUSCH (Mb/s)	Median PUSCH (Mb/s)	Standard Deviation (Mb/s)	Min PUSCH (Mb/s)	Max PUSCH (Mb/s)
PSCR MN	0.14	0.12	0.1	0.0	0.5
COW 8 W	15.6	16.2	2.0	0.8	18.6
COW 40 W	15.7	16.1	2.1	0.8	18.5
SCDA 5 W	12.0	12.1	1.2	25.5	13.4
SCDA 5 W+ PSCR MN	9.3	9.2	2.0	5.4	14.2
SCDA 5 W + COW 8 W+ PSCR MN	10.8	12.5	4.0	1.0	18.1
SCDA 5 W + COW 40 W + PSCR MN	11.6	12.7	4.3	2.9	18.8
SCDAS	12.1	12.2	1.1	0.0	12.5

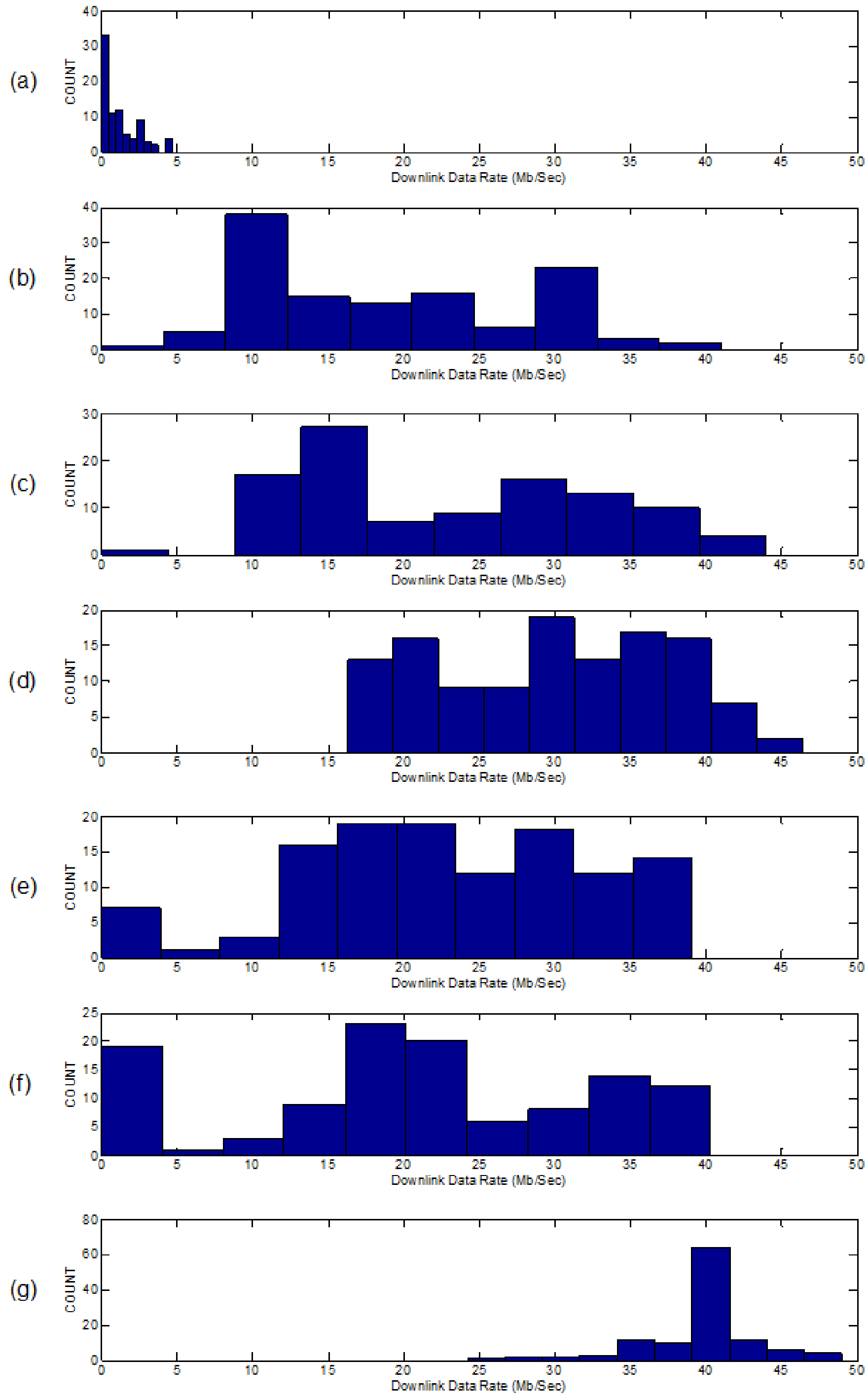

Figure 95. Level 1 histograms of PDSCH for different coverage combinations with a UDP downlink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas and PSCR MN, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (g) small cell feeding a four-antenna passive DAS system.

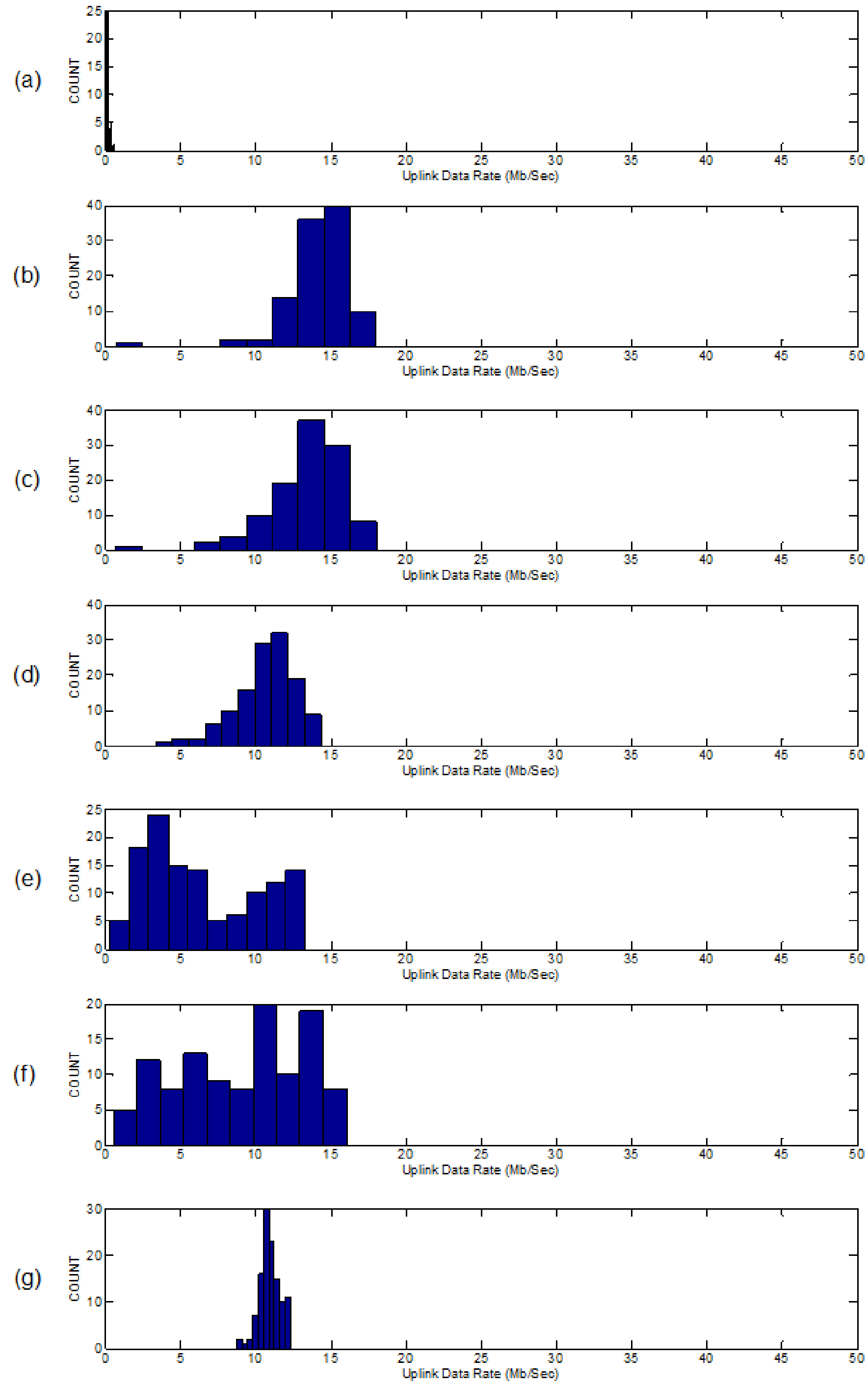

Figure 96. Level 1 histograms of PUSCH for different coverage combinations with a UDP uplink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas and PSCR MN ,(e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (g) small cell feeding a four-antenna passive DAS system.

Table 43. Level 1 PDSCH statistics for a UDP downlink data flow.

Coverage Combination	**Mean PDSCH (Mb/s)**	**Median PDSCH (Mb/s)**	**Standard Deviation (Mb/s)**	**Min PDSCH (Mb/s)**	**Max PDSCH (Mb/s)**
PSCR MN	1.2	0.6	1.2	0.0	4.7
COW 8 W	18.9	18.2	9.1	0.0	41.0
COW 40 W	23.0	21.8	9.7	0.0	44.0
SCDA 5 W+ PSCR MN	29.9	30.8	7.8	16.3	46.4
SCDA 5 W + COW 8 W+ PSCR MN	22.8	21.8	9.8	0.0	39.1
SCDA 5 W + COW 40 W + PSCR MN	20.8	20.7	12.0	0.0	40.3
SCDAS	39.8	40.5	3.8	24.2	49.0

Table 44. Level 1 PUSCH statistics for a UDP uplink data flow.

Coverage Combination	**Mean PUSCH (Mb/s)**	**Median PUSCH (Mb/s)**	**Standard Deviation (Mb/s)**	**Min PUSCH (Mb/s)**	**Max PUSCH (Mb/s)**
PSCR MN	0.15	0.13	0.11	0.0	0.6
COW 8 W	14.2	14.4	2.2	0.7	18.0
COW 40 W	13.4	13.8	2.5	0.7	18.0
SCDA 5 W+ PSCR MN	10.7	11.0	2.0	3.3	14.4
SCDA 5 W + COW 8 W+ PSCR MN	6.5	5.4	3.7	0.3	13.3
SCDA 5 W + COW 40 W + PSCR MN	9.0	9.9	4.2	0.5	16.1
SCDAS	10.9	10.9	0.7	8.8	12.3

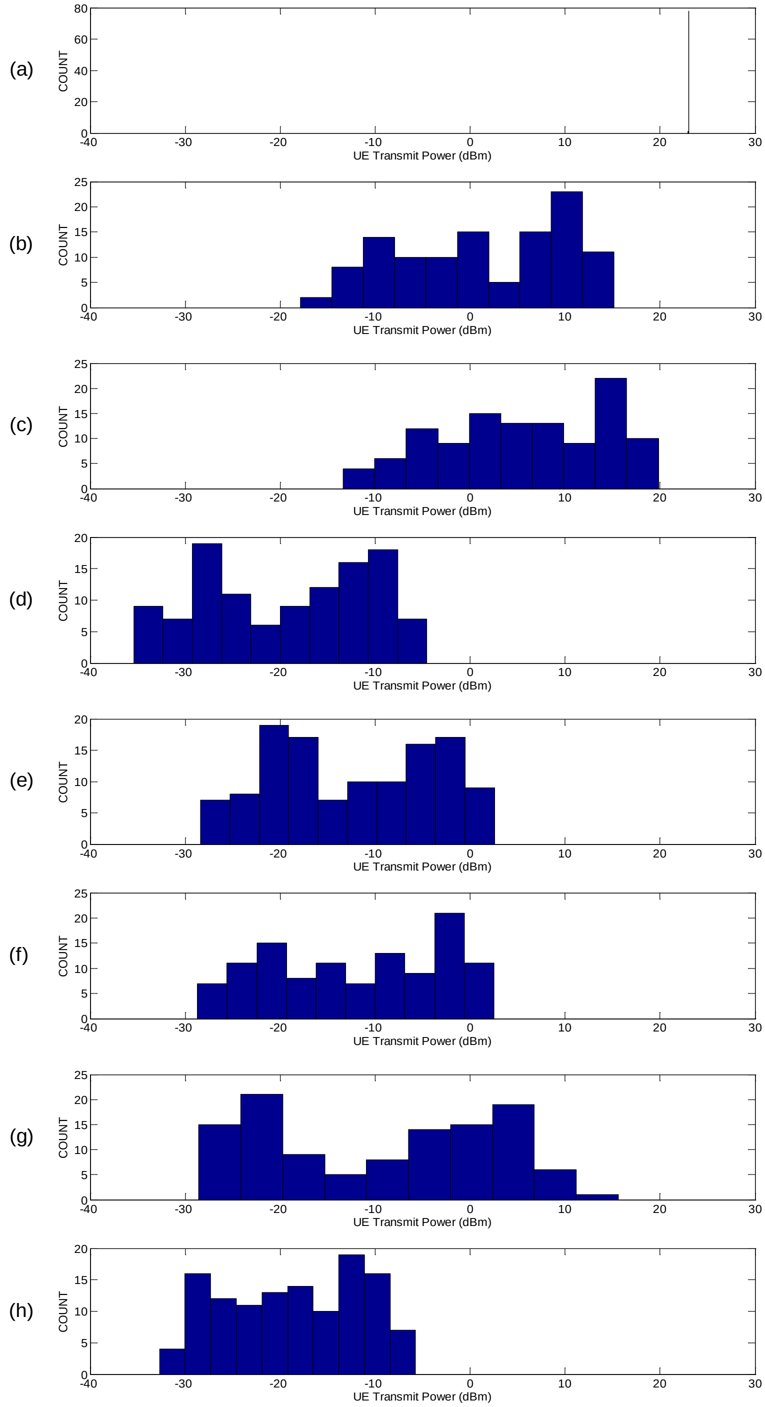

Figure 97. Level 1 histograms of UE transmit power for different coverage combinations with a TCP downlink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas, (e) small cell at 5 W with discrete antennas and PSCR MN , (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (g) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (h) small cell feeding a four-antenna passive DAS system.

(a)
(b)
(c)
(d)
(e)
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(h)

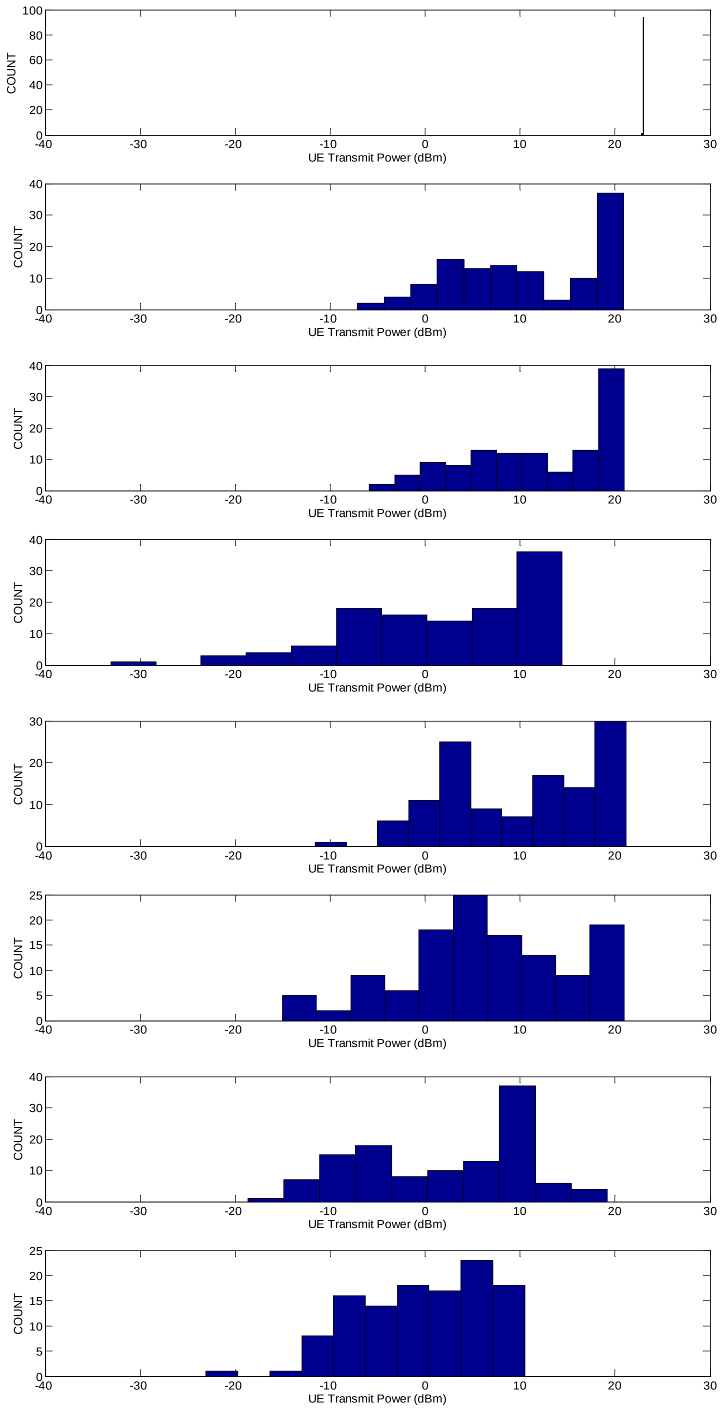

Figure 98. Level 1 histograms of UE transmit power for different coverage combinations with a TCP uplink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas, (e) small cell at 5 W with discrete antennas and PSCR MN , (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (g) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (h) small cell feeding a four-antenna passive DAS system.

Table 45. Level 1 UE transmit power statistics for a TCP downlink data flow.

Coverage Combination	Mean UEtpwr (dBm)	Median UEtpwr (dBm)	Standard Deviation (dBm)	Min UEtpwr (dBm)	Max UEtpwr (dBm)
PSCR MN	23.0	23.0	0.01	22.9	23.0
COW 8 W	1.3	0.2	8.9	-17.9	15.2
COW 40 W	5.7	6.1	8.7	-13.4	19.8
SCDA 5 W	-19.4	-18.5	8.8	-35.4	-4.5
SCDA 5 W+ PSCR MN	-12.3	-12.7	8.7	-28.4	2.6
SCDA 5 W + COW 8 W+ PSCR MN	-11.8	-11.3	9.1	-28.7	2.5
SCDA 5 W + COW 40 W + PSCR MN	-9.5	-7.2	12.0	-28.6	15.6
SCDAS	-18.5	-18.4	7.2	-32.7	-5.7

Table 46. Level 1 UE transmit power statistics for a TCP uplink data flow.

Coverage Combination	Mean UEtpwr (dBm)	Median UEtpwr (dBm)	Standard Deviation (dBm)	Min UEtpwr (dBm)	Max UEtpwr (dBm)
PSCR MN	23.0	23.0	0.03	22.8	23.0
COW 8 W	11.0	10.3	7.8	-7.1	20.9
COW 40 W	12.2	12.0	7.6	-5.9	21.0
SCDA 5 W	2.0	3.6	9.8	-33.1	14.4
SCDA 5 W+ PSCR MN	10.0	11.4	8.0	-11.6	21.2
SCDA 5 W + COW 8 W+ PSCR MN	6.7	6.4	8.9	-15.0	21.0
SCDA 5 W + COW 40 W + PSCR MN	2.1	4.1	8.7	-18.7	19.2
SCDAS	-0.2	0.4	6.7	-23.1	10.5

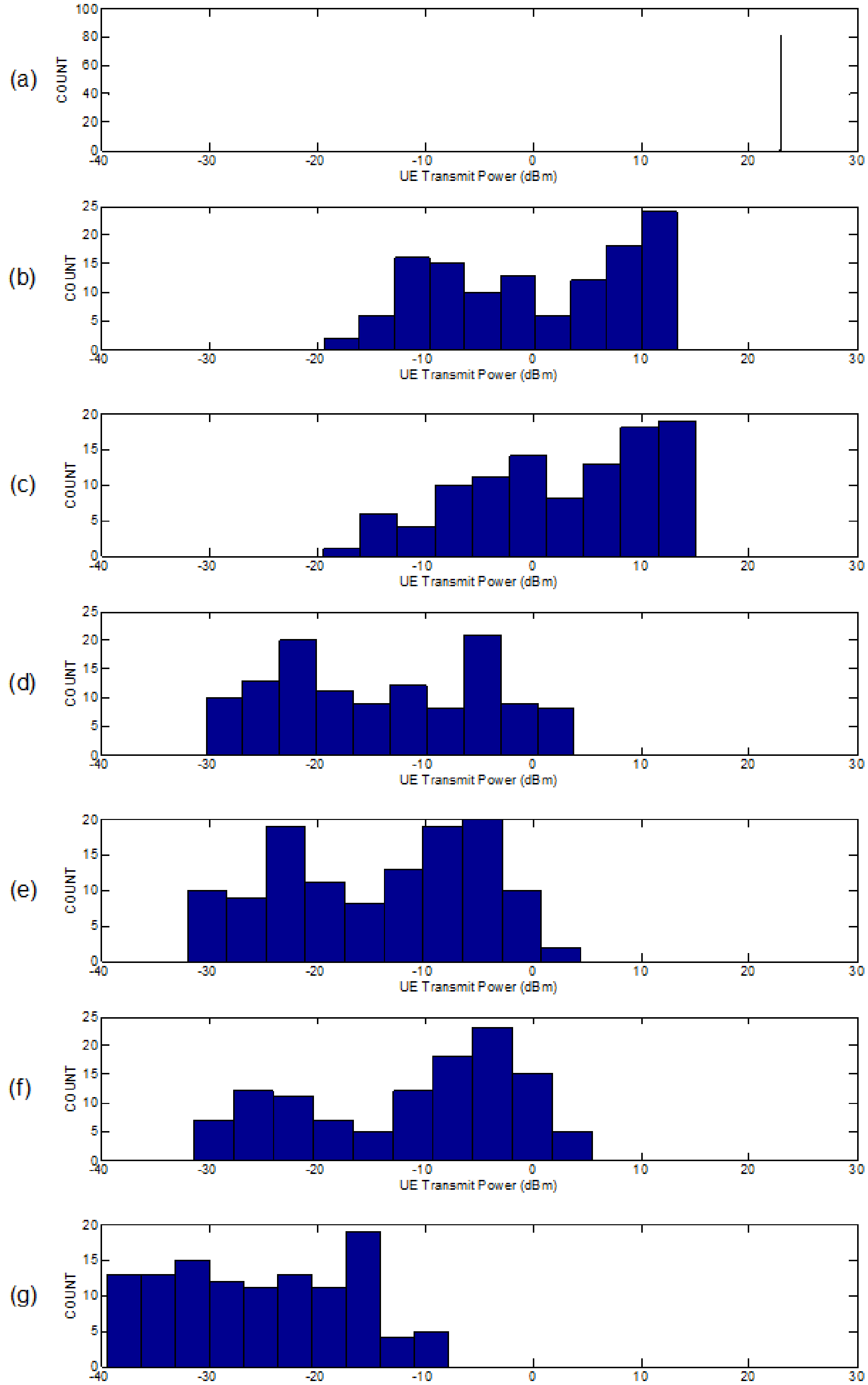

Figure 99. Level 1 histograms of UE transmit power for different coverage combinations with a UDP downlink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas and PSCR MN ,(e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (g) small cell feeding a four-antenna passive DAS system.

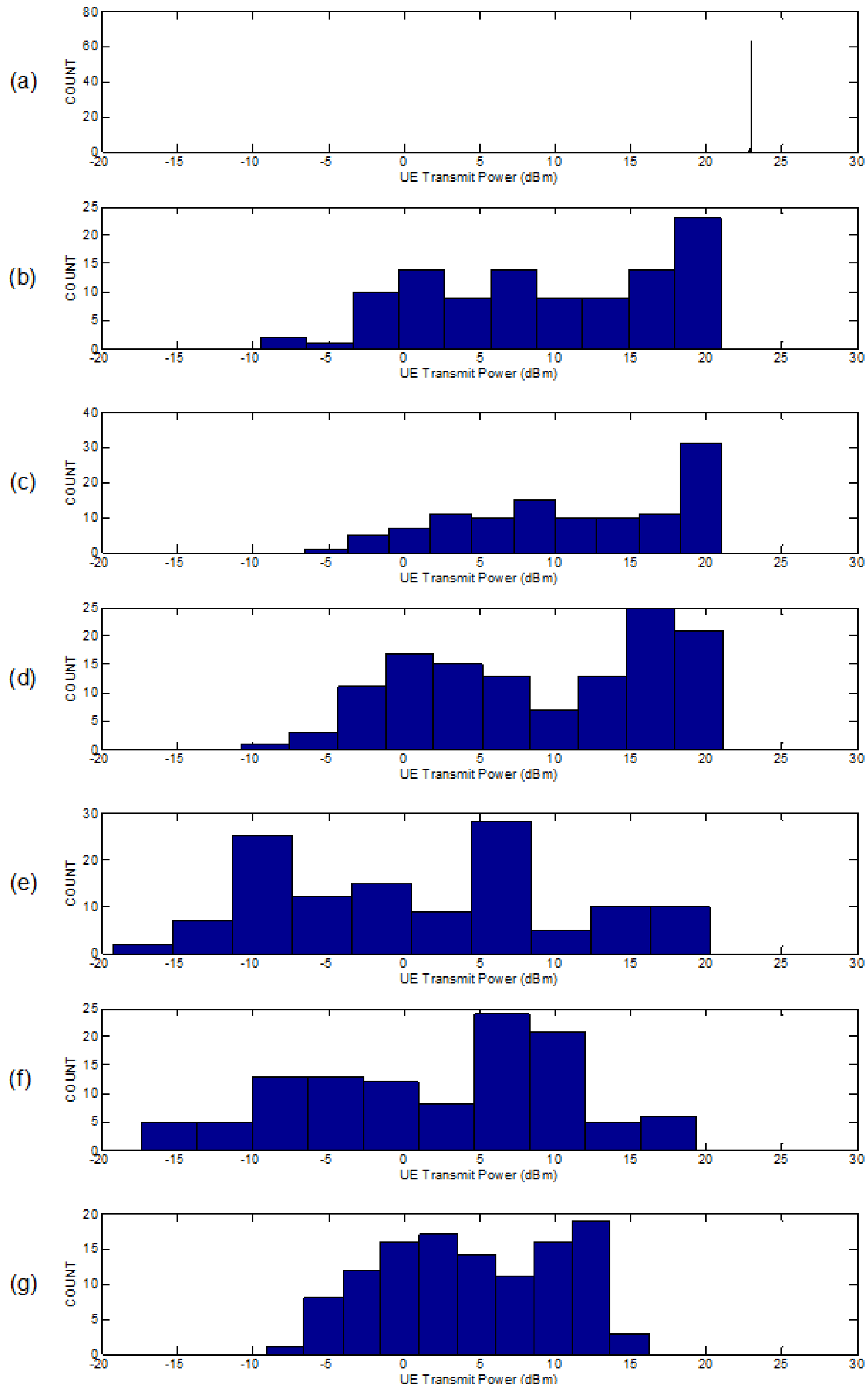

Figure 100. Level 1 histograms of UE transmit power for different coverage options with a UDP uplink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas and PSCR MN ,(e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W, (g) small cell feeding a four-antenna passive DAS system.

Table 47. Level 1 UE transmit power statistics for a UDP downlink data flow.

Coverage Combination	Mean UEtpwr (dBm)	Median UEtpwr (dBm)	Standard Deviation (dBm)	Min UEtpwr (dBm)	Max UEtpwr (dBm)
PSCR MN	23.0	23.0	0.01	22.9	23.0
COW 8 W	0.0	-0.3	-0.27	-19.4	13.3
COW 40 W	2.7	3.0	5.6	-19.4	15.0
SCDA 5 W+ PSCR MN	-13.9	-14.1	9.5	-30.3	3.8
SCDA 5 W + COW 8 W+ PSCR MN	-14.3	-12.5	9.3	-32.0	4.4
SCDA 5 W + COW 40 W + PSCR MN	-11.3	-8.5	10.1	-31.5	5.5
SCDAS	-25.1	-25.2	8.5	-39.5	-7.9

Table 48. Level 1 UE transmit power statistics for a UDP uplink data flow.

Coverage Combination	Mean UEtpwr (dBm)	Median UEtpwr (dBm)	Standard Deviation (dBm)	Min UEtpwr (dBm)	Max UEtpwr (dBm)
PSCR MN	23.0	23.0	0.03	22.9	23.0
COW 8 W	9.6	9.5	8.0	-9.5	21.0
COW 40 W	11.3	10.8	7.4	-6.5	21.0
SCDA 5 W+ PSCR MN	9.3	9.9	8.0	-10.8	21.1
SCDA 5 W + COW 8 W+ PSCR MN	1.1	1.1	9.7	-19.3	20.3
SCDA 5 W + COW 40 W + PSCR MN	2.3	4.6	8.8	-17.4	19.3
SCDAS	4.6	4.2	5.8	-9.1	16.2

3.4 DLC Level 2 Measured Results

The level 2 tests were conducted on the most extended and complex walk test path in the DLC. The walk test path is both contained within the building core and also crosses over to the engineering center on an interconnecting bridge. This bridge is located on the southwest corner of the DLC and it is oriented along an east-west axis. The bridge is a hallway appendage shown on the lower left portion of the walk test maps. We collected data for both uplink and downlink data flows using both TCP and UDP.

Results were obtained on level 2 for the following seven coverage combinations:

- PSCR MN only
- SCDA only at 5 W input
- COW only at 8 W
- COW only at 40 W

- PSCR MN + SCDA at 5 W (TCP only)
- PSCR MN +SCDA at 5 W + COW at 40 W
- PSCR MN +SCDA at 5 W + COW at 8 W

Figures 101–107 show maps of the serving cell RSRP as a function of coverage for a TCP downlink data flow. The corresponding RSRP histograms are plotted in Figures 108–111. Summary statistics are given in Tables 49–52. Figure 101 shows the PSCR MN coverage and the signal levels are noticeably stronger than those obtained on level 1. The improvement is approximately 10 dB, and this is due to reduced path blockage of the Green Mountain eNB by the Engineering Center.

The use of the COW at transmit power levels of either 8 W or 40 W provides significantly improved coverage on the south and east side of the DLC. The coverage improvements for the COW at 8 W are marginal in the west hallway, and those in the interconnecting bridge are also marginal. Noticeable improvements occur when the power is increased to 40 W. The SCDA yields signal levels similar to that of the COW at 40 W in the east, south and north hallways—all contained within the core structure of the DLC. The SCDA provides inferior coverage on the interconnecting bridge due to blocking effects of the outer walls of the DLC and the presence of low-E glass on the bridge windows.

The best overall signal levels are obtained using the combination of the SCDA, the COW at 40 W, and the PSCR MN. An SCDAS system deployed on the second floor would provide an even better solution, but the constraints of the project precluded exploration of this option.

Figures 112–115 and Tables 53–56 show the CINR results for both uplink and downlink data flows using both the TCP and UDP transfer protocols. When coverage is provided by the PSCR MN, we see a significant improvement (approximately 10 dB) over the corresponding level 1 results—this tracks the improvements in the absolute signal levels (RSRP). However, the resulting values still indicate poor system performance. When the COW is active at transmit power levels of either 8 W or 40 W, the results improve dramatically in both the east and south sides of the DLC. The improvements on the west side and the interconnecting bridge are not nearly as pronounced, and performance is still poor in these two sections of the walk path. The SCDA system transmitting at 5 W provides improved coverage over most of the walk path within the building core, but we see degraded performance in both the bridge section and on the southeast corner of the walk route. This is caused by increased path losses between the small cell and the UE. The best overall CINR performance is seen when coverage is provided by the combination of the small cell, COW, and the PSCR MN.

The PDSCH downlink data rates are given in Figures 116 and 118 for TCP and UDP, respectively. Summary statistics are given in Tables 57 and 59.The downlink data rates on level 2 are markedly better than those on level 1 when the PSCR MN is providing coverage. In this case, maximum data rates in excess of 13 Mb/s are seen for TCP, and 21 Mb/s using UDP. This can be attributed to the better signal quality and reduced path losses between the Green Mountain eNB and the UE.

When the COW provides coverage at 40 W, data rates improve, with resulting maximum PDSCH data rates above 39 Mb/s for TCP and 40 Mb/s for UDP. These high rates occur in the eastern hallway of the DLC, near where the COW is located, and reduced rates are seen on the south and west hallways, as well as on the bridge. When the SCDA system is providing coverage, maximum downlink data rates in excess of 35 Mb/s are seen with TCP. Low data rates still occur on the bridge due to high path losses between the small cell and the UE on this section of the test path. Adding the macro network to the small cell coverage produces multiple handovers in the bridge section of the walk path. This accounts for the increased occurrences of low data rates, as can be seen by comparing Figures 116(d) and 116(e).

When the combination of the small cell, the COW at a transmit power of 8 W, and the PSCR MN are providing coverage, there are high occurrences of low data rates. This is caused by multiple handovers among the three coverage elements. In order to prevent this, one would need to perform careful optimization of the hysteresis and offset settings of the Green Mountain eNB, the COW, and the small cell. We also see this effect for the same coverage combination when the COW is transmitting at 40 W. In this case, there are fewer instances of low data rates, since handovers occur only between the small cell and the COW. The increased transmit power of the COW completely swamps out the macro network. The best overall downlink data rate performance is seen when the COW alone is providing coverage and it is transmitting at 40 W.

The TCP and UDP PUSCH data rate results are depicted in Figures 117 and 119 respectively. Statistical summaries are provided in Tables 58 and 60.The general trends as a function of coverage are similar to those seen for the downlink data flows. When coverage is provided by the PSCR MN, the resulting uplink data rates are once again significantly improved over the corresponding level 1 results. Uplink data rate performance is best when the COW provides coverage, and the results are not strongly affected by the transmit power level. Uplink data rates nearly as good as those with the COW occur when the small cell is providing in-building coverage. When combinations of the small cell, COW, and macro network are used, low data rates are encountered in portions of the walk route where handovers occur.

The UE transmitted power levels for uplink and downlink data flows are presented in Figures 120–123 and Tables 61–64 for both TCP and UDP. A study of these results indicates that an uplink data flow results in higher transmitted power levels—an increased data payload requires more power. When the PSCR MN provides coverage with an uplink data flow, the UE transmits at the highest levels—this would translate into the maximum battery drain on a portable Band 14 device.

A study of Figures 121 and 123 reveals some improvements when the COW is used to provide in-building coverage. The UE is able to reduce power on the east hallway because of reduced path losses, but it must increase power on the remaining portions of the walk path, due to blockage effects of both interior and exterior walls. Similar results are seen for a TCP uplink data flow when the SCDA option is used for in-building coverage. The combination of the small cell, COW, and PSCR MN yield similar results as well.

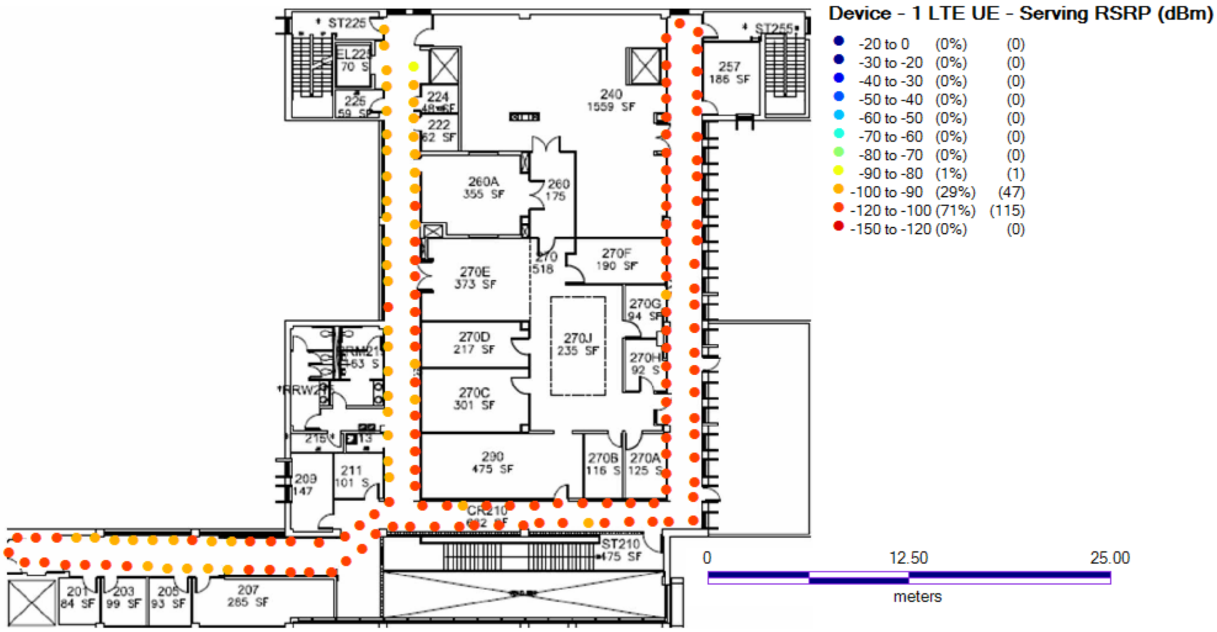

Figure 101. Level 2 reference signal received power (RSRP) for a TCP downlink data flow with the PSCR MN. The direction of top of the floor plan is north.

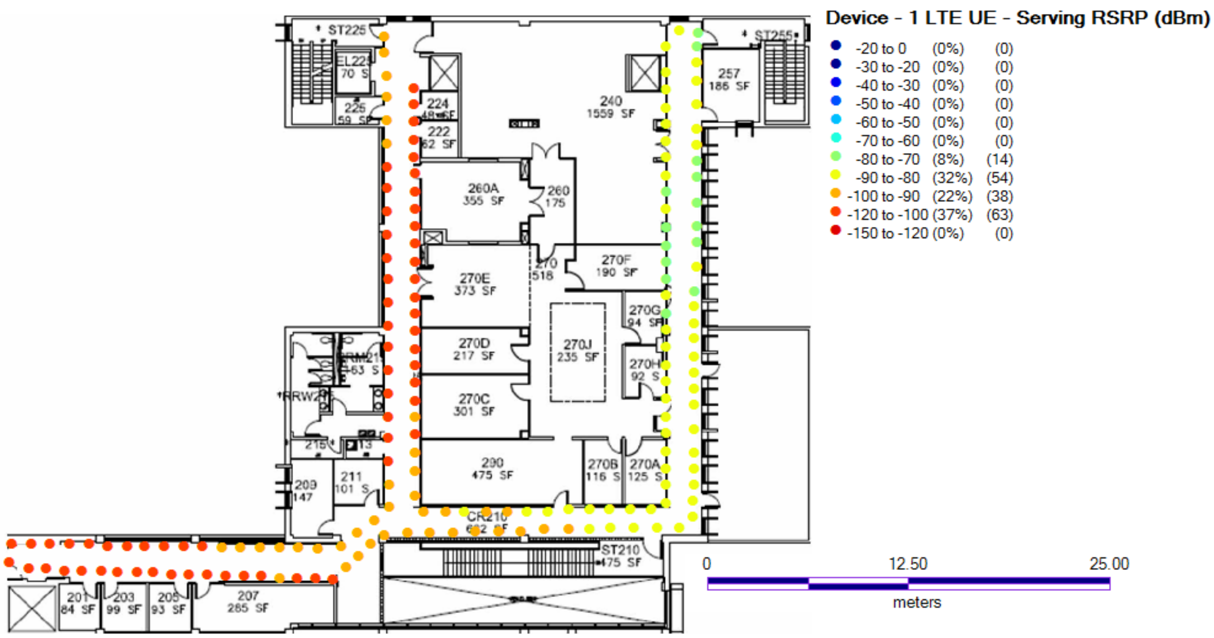

Figure 102. Level 2 reference signal received power (RSRP) for a TCP downlink data flow with a COW at 8 W. The direction of top of the floor plan is north.

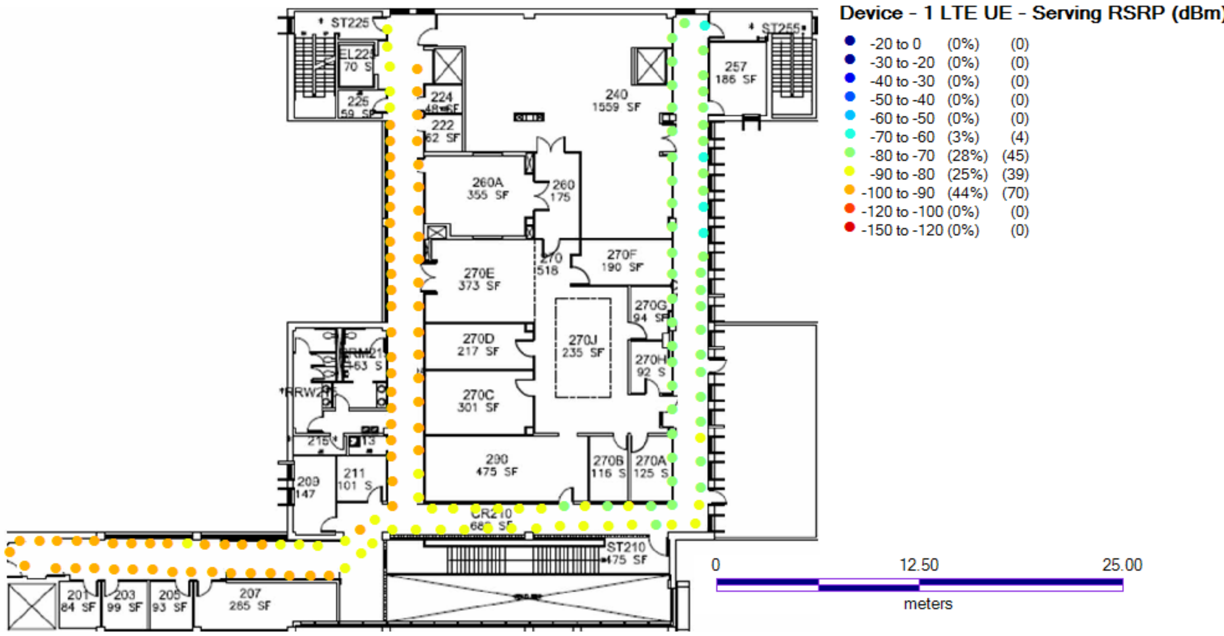

Figure 103. Level 2 reference signal received power (RSRP) for a TCP downlink data flow with a COW at 40 W. The direction of top of the floor plan is north.

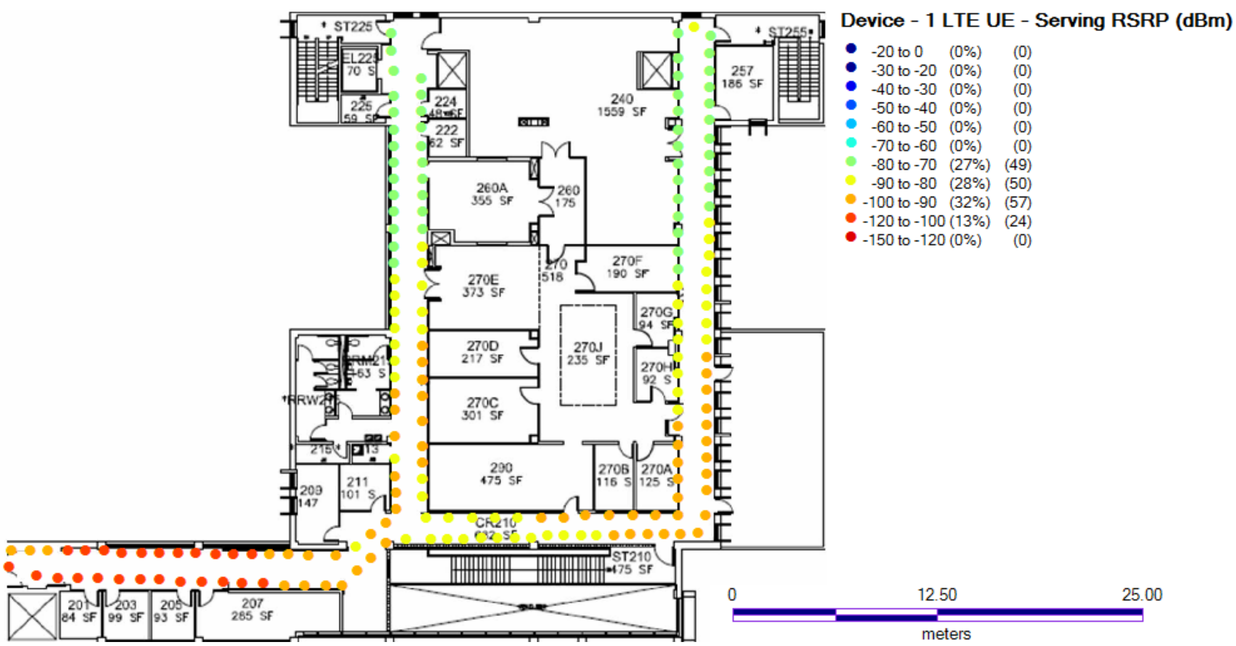

Figure 104. Level 2 reference signal received power (RSRP) for a TCP downlink data flow with a small cell at 5 W and discrete antennas. The direction of top of the floor plan is north.

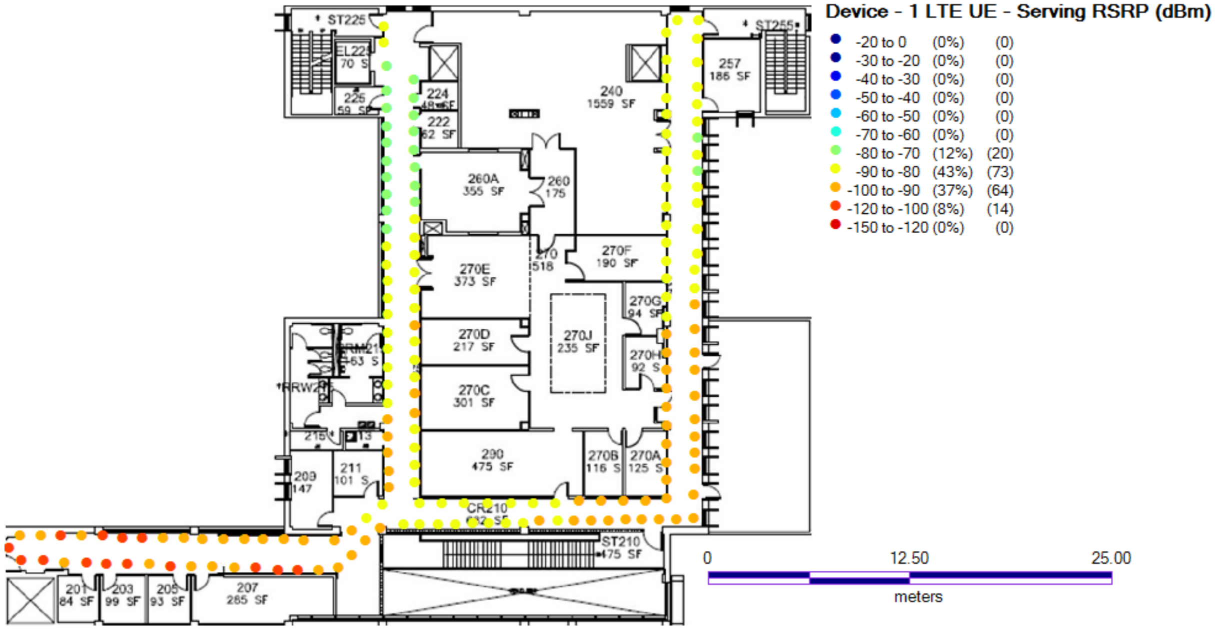

Figure 105. Level 2 reference signal received power (RSRP) for a TCP downlink data flow with a small cell at 5 W and the PSCR MN. The direction of top of the floor plan is north.

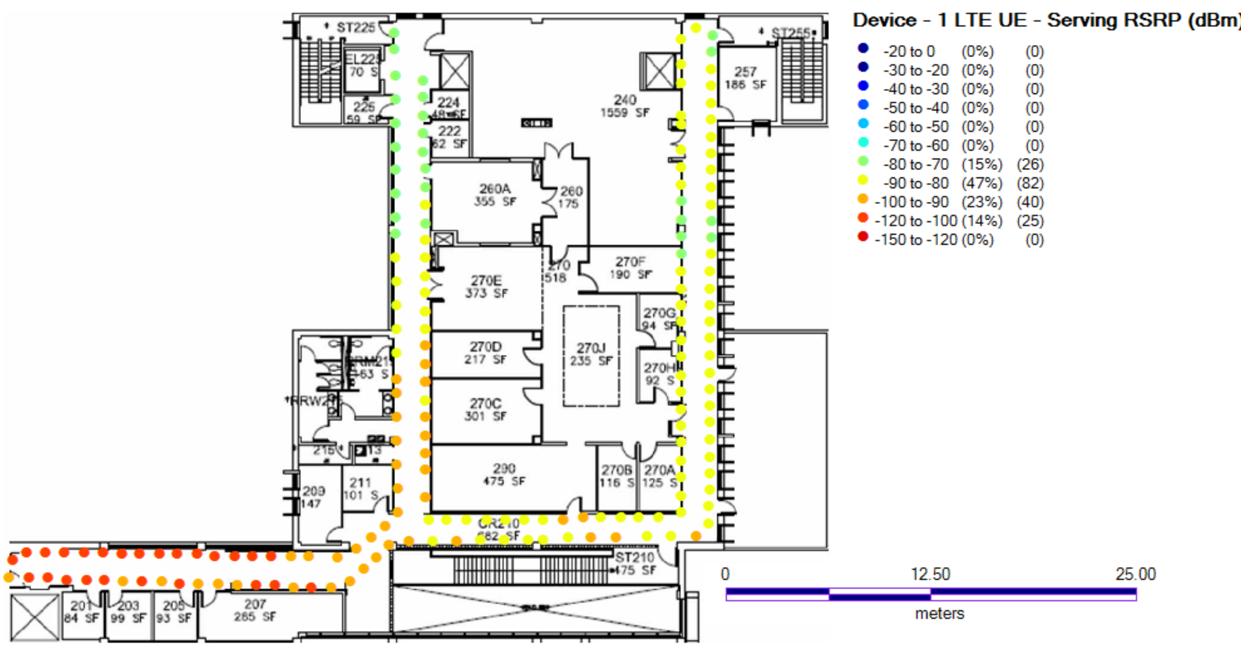

Figure 106. Level reference signal received power (RSRP) for TCP downlink data flow with a small cell at 5 W, COW at 8 W, and the PSCR MN. The direction of top of the floor plan is north.

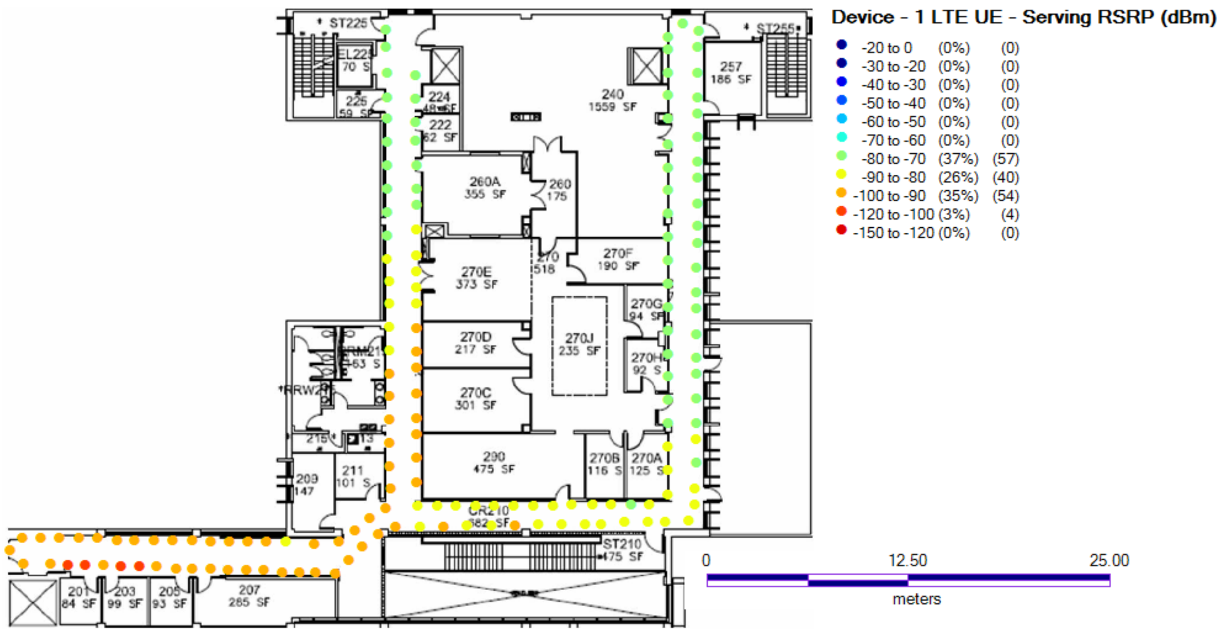

Figure 107. Level 2 reference signal received power (RSRP) for a TCP downlink data flow with a small cell at 5 W, COW at 40 W, and the PSCR MN. The direction of top of the floor plan is north.

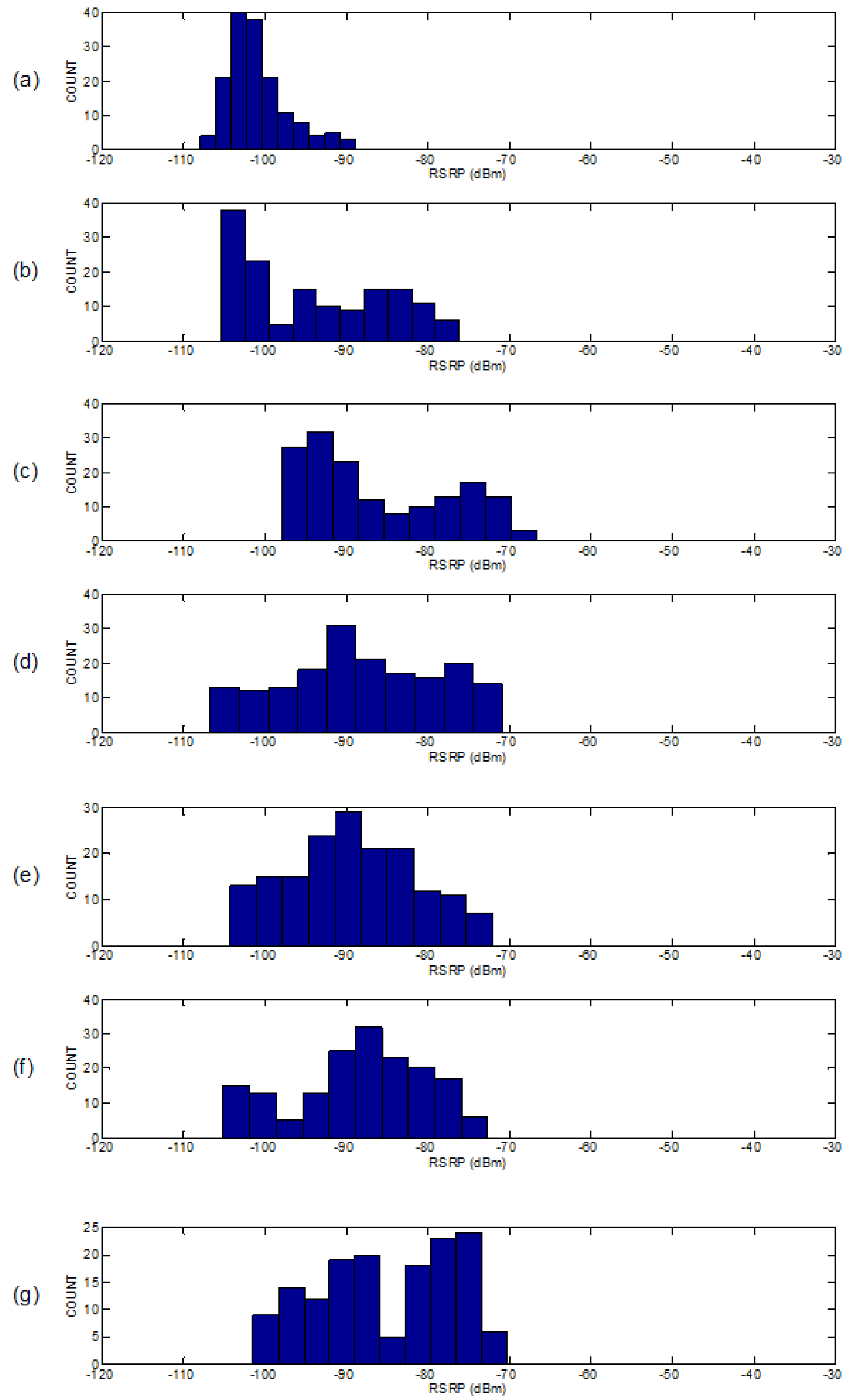

Figure 108. Level 2 histograms of serving cell RSRP with different coverage combinations for a TCP downlink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas, (e) small cell at 5 W with discrete antennas and PSCR MN, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (g) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

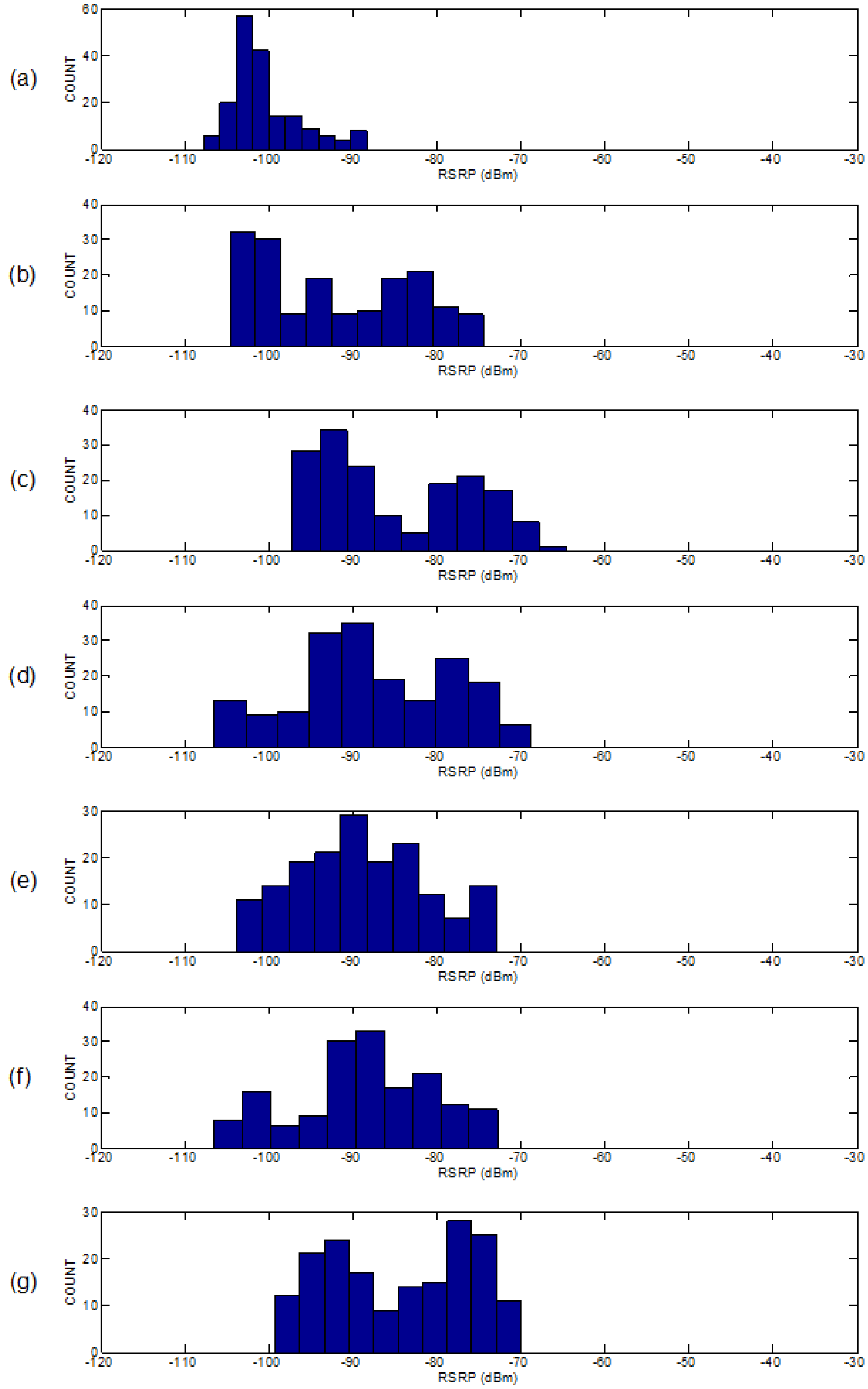

Figure 109. Level 2 histograms of serving cell RSRP with different coverage combinations for a TCP uplink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas, (e) small cell at 5 W with discrete antennas and PSCR MN, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (g) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

Table 49. Level 2 RSRP statistics for a TCP downlink data flow.

Coverage Combination	**Mean RSRP (dBm)**	**Median RSRP (dBm)**	**Standard Deviation (dBm)**	**Min RSRP (dBm)**	**Max RSRP (dBm)**
PSCR MN	-100.8	-101.5	3.7	-108.0	-88.7
COW 8 W	-93.9	-95.8	8.8	-105.3	-76.2
COW 40 W	-86.0	-88.9	8.8	-98.0	-66.7
SCDA 5 W	-88.0	-88.6	9.5	-106.7	-70.8
SCDA 5 W+ PSCR MN	-89.2	-89.5	7.7	-104.3	-72.1
SCDA 5 W + COW 8 W+ PSCR MN	-88.4	-87.8	8.1	-105.2	-72.7
SCDA 5 W + COW 40 W + PSCR MN	-85.2	-85.4	8.3	-101.5	-70.3

Table 50. Level 2 RSRP statistics for a TCP uplink data flow.

Coverage Combination	**Mean RSRP (dBm)**	**Median RSRP (dBm)**	**Standard Deviation (dBm)**	**Min RSRP (dBm)**	**Max RSRP (dBm)**
PSCR MN	-100.5	-101.7	4.2	-107.9	-88.4
COW 8 W	-92.1	-94.9	9.1	-104.7	-74.5
COW 40 W	-85.0	-88.4	8.6	-97.3	-64.6
SCDA 5 W	-87.7	-89.3	9.1	-106.6	-68.8
SCDA 5 W+ PSCR MN	-89.1	-89.7	7.8	-103.9	-72.9
SCDA 5 W + COW 8 W+ PSCR MN	-88.7	-89.0	8.3	-106.6	-72.8
SCDA 5 W + COW 40 W + PSCR MN	-84.4	-83.1	8.4	-99.4	-70.0

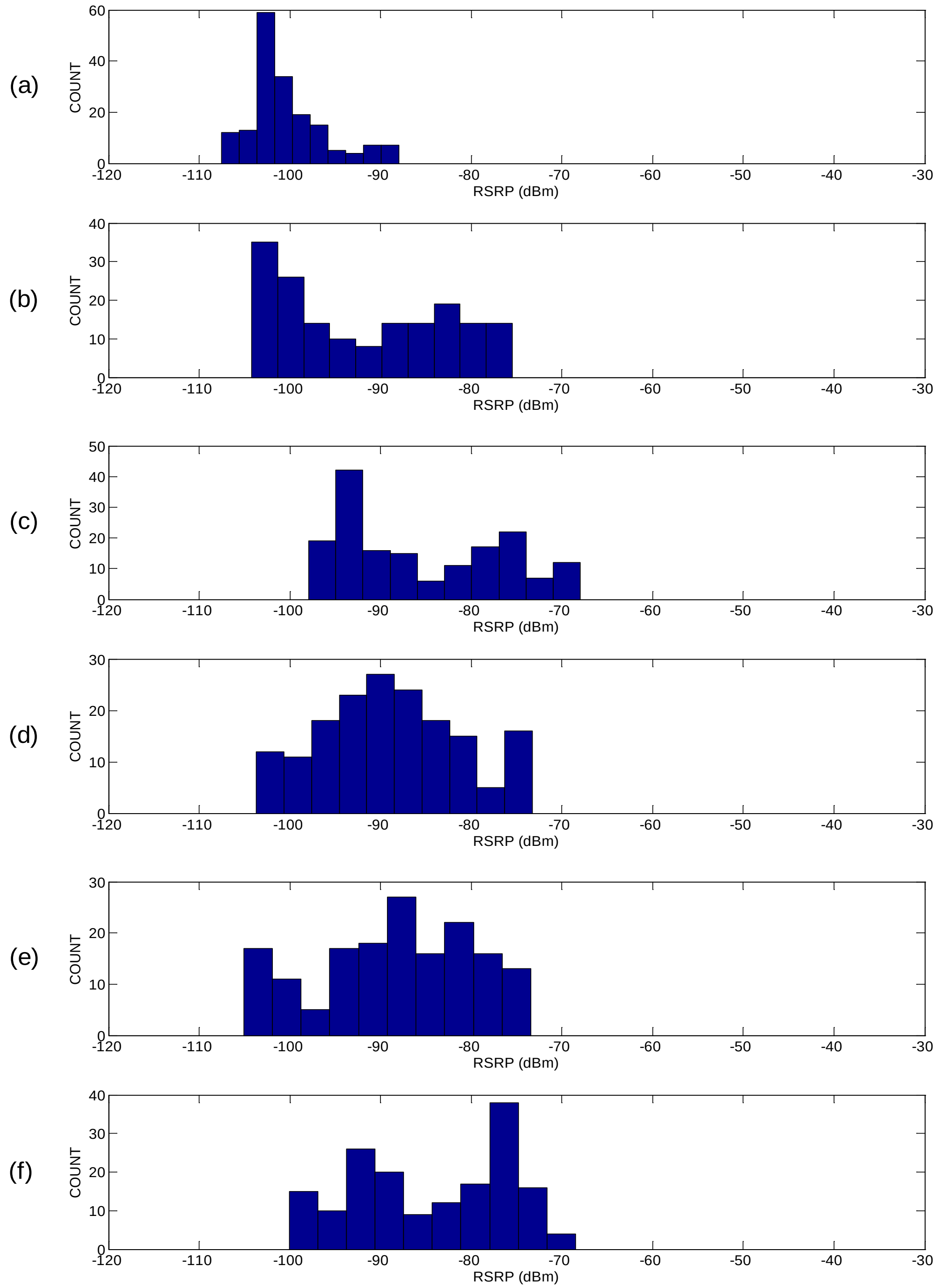

Figure 110. Level 2 histograms of serving cell RSRP with different coverage combinations for a UDP downlink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas and PSCR MN, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

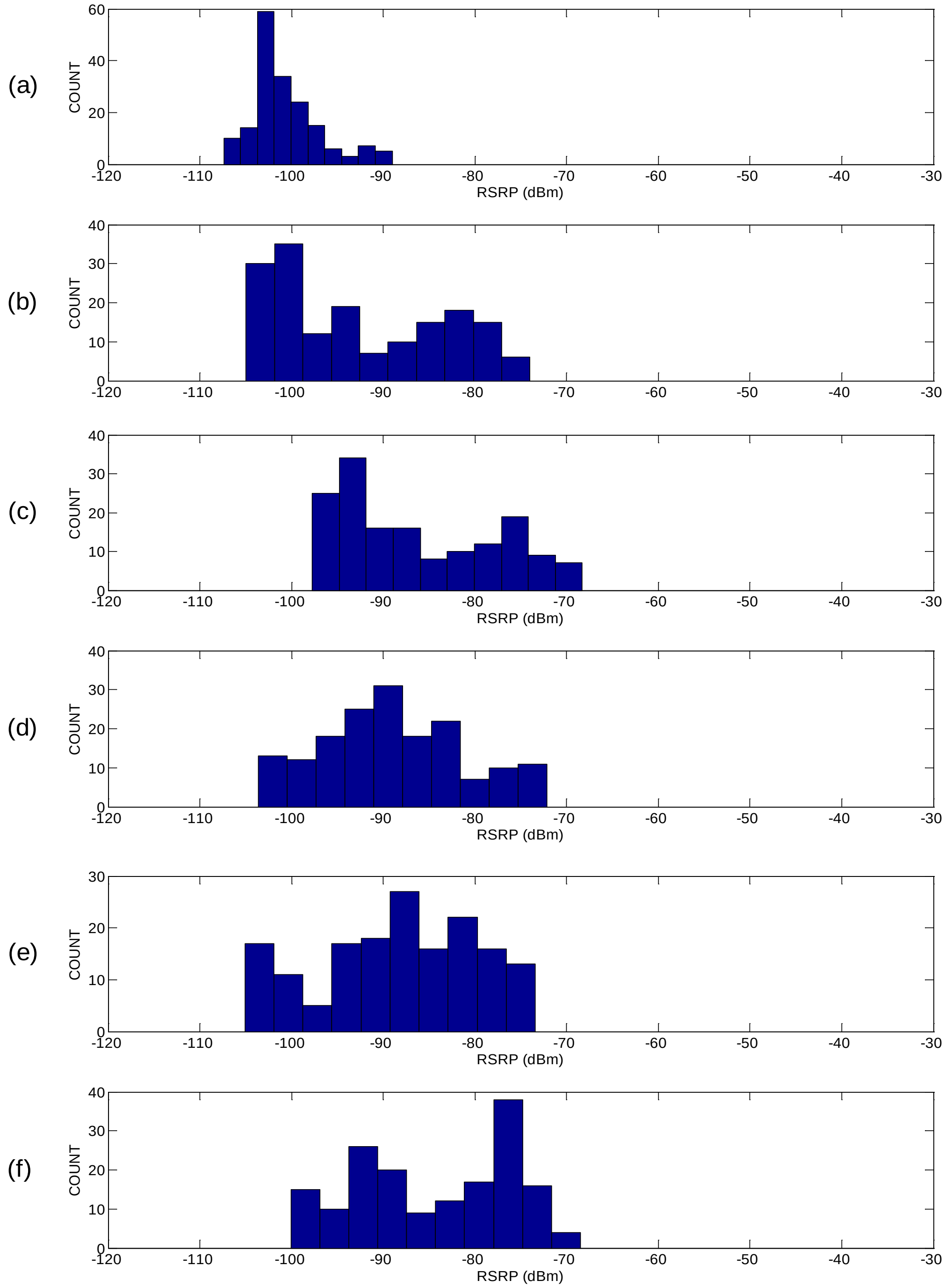

Figure 111. Level 2 histograms of serving cell RSRP with different coverage combinations for a UDP uplink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas and PSCR MN, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

Table 51. Level 2 RSRP statistics for a UDP downlink data flow.

Coverage Combination	Mean RSRP (dBm)	Median RSRP (dBm)	Standard Deviation (dBm)	Min RSRP (dBm)	Max RSRP (dBm)
PSCR MN	-100.3	-101.4	4.3	-107.5	-88.0
COW 8 W	-91.8	-39.0	9.1	-104.2	-75.5
COW 40 W	-85.4	-88.2	8.8	-98.0	-67.9
SCDA 5 W+ PSCR MN	-88.4	-89.1	7.7	-103.7	-73.3
SCDA 5 W + COW 8 W+ PSCR MN	-88.3	-87.1	8.7	-105.1	-73.4
SCDA 5 W + COW 40 W + PSCR MN	-84.4	-83.4	8.4	-100.1	-68.5

Table 52. Level 2 RSRP statistics for a UDP downlink data flow.

Coverage Combination	Mean RSRP (dBm)	Median RSRP (dBm)	Standard Deviation (dBm)	Min RSRP (dBm)	Max RSRP (dBm)
PSCR MN	-100.7	-101.7	3.8	-107.4	-89.0
COW 8 W	-92.5	-94.1	9.0	-105.0	-74.0
COW 40 W	-86.2	-88.5	5.6	-97.8	-68.3
SCDA 5 W+ PSCR MN	-88.9	-89.1	7.9	-103.7	-72.1
SCDA 5 W + COW 8 W+ PSCR MN	-87.6	-86.1	9.1	-106.0	-71.9
SCDA 5 W + COW 40 W + PSCR MN	-84.3	-83.8	8.3	-99.0	-67.8

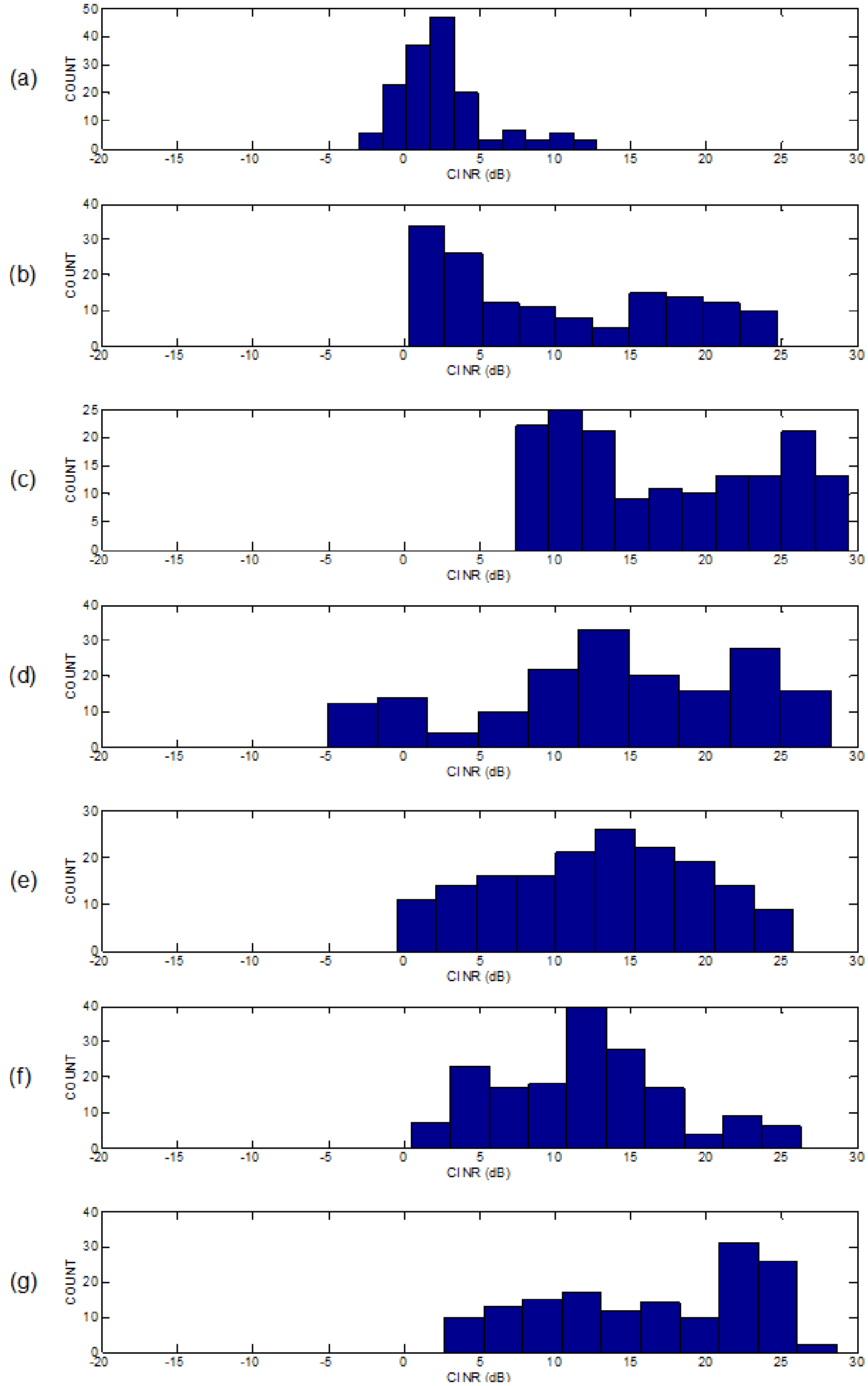

Figure 112. Level 2 histograms of CINR with different coverage combinations for a TCP downlink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas, (e) small cell at 5 W with discrete antennas and PSCR MN, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (g) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

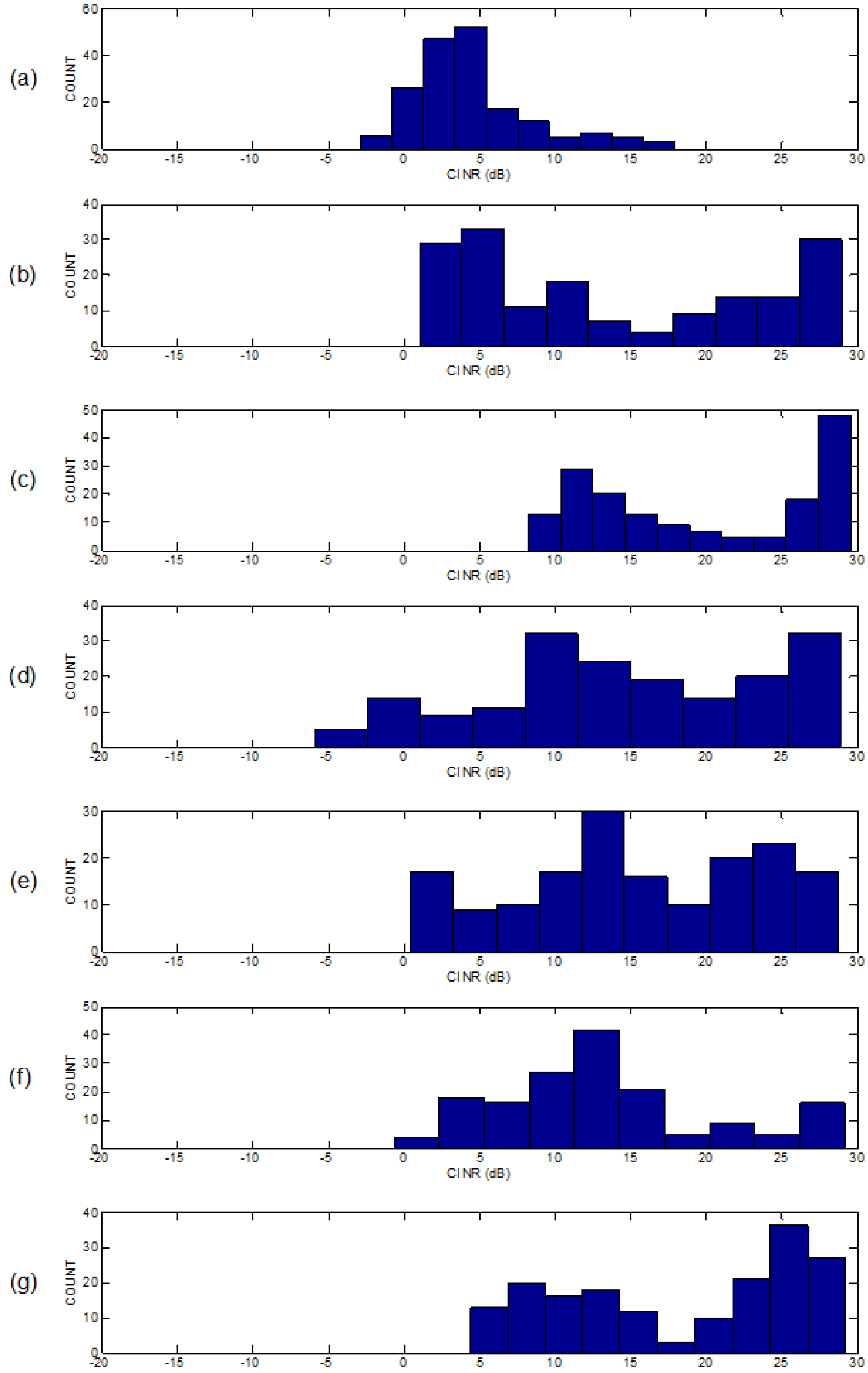

Figure 113. Level 2 histograms of CINR with different coverage combinations for a TCP uplink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas, (e) small cell at 5 W with discrete antennas and PSCR MN, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (g) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

Table 53. Level 2 CINR statistics for a TCP downlink data flow.

Coverage Combination	Mean CINR (dB)	Median CINR (dB)	Standard Deviation (dB)	Min CINR (dB)	Max CINR (dB)
PSCR MN	2.6	2.2	3.1	-3.0	12.8
COW 8 W	10.0	7.9	7.6	0.3	24.7
COW 40 W	17.5	16.4	6.8	7.4	29.4
SCDA 5 W	14.0	14.1	8.8	-5.1	28.2
SCDA 5 W+ PSCR MN	13.8	13.3	6.7	-0.5	25.8
SCDA 5 W + COW 8 W+ PSCR MN	12.8	12.2	5.7	0.5	26.2
SCDA 5 W + COW 40 W + PSCR MN	16.3	17.3	7.0	2.7	28.6

Table 54. Level 2 CINR statistics for a TCP uplink data flow.

Coverage Combination	Mean CINR (dB)	Median CINR (dB)	Standard Deviation (dB)	Min CINR (dB)	Max CINR (dB)
PSCR MN	4.5	3.7	4.0	-2.9	17.9
COW 8 W	14.0	11.2	9.6	1.1	29.0
COW 40 W	19.8	18.1	7.4	8.2	29.6
SCDA 5 W	14.7	13.9	9.1	-5.9	28.9
SCDA 5 W+ PSCR MN	15.4	14.7	7.9	0.5	28.7
SCDA 5 W + COW 8 W+ PSCR MN	13.2	12.3	7.2	-0.7	29.2
SCDA 5 W + COW 40 W + PSCR MN	18.4	20.7	7.8	4.4	29.2

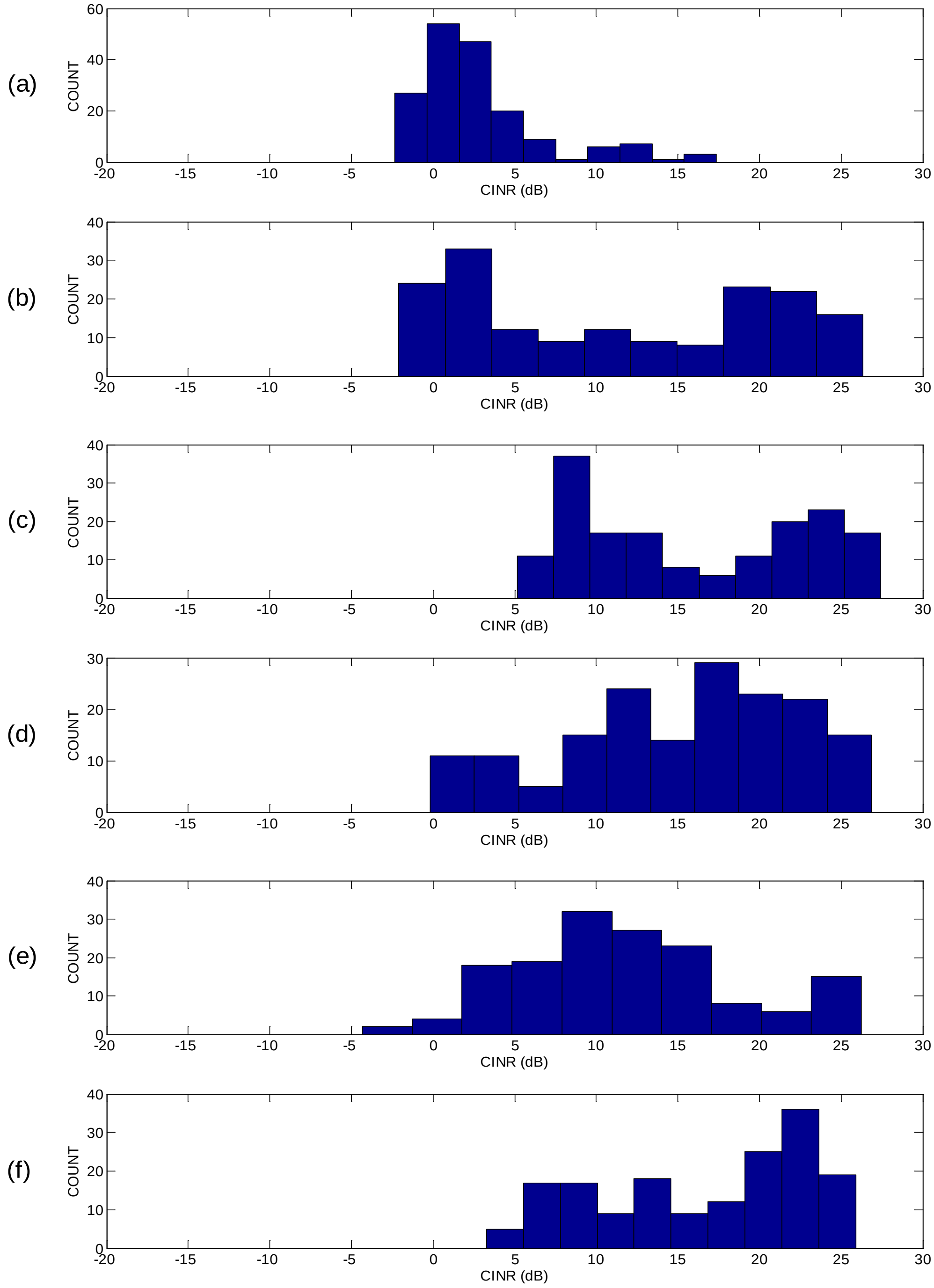

Figure 114. Level 2 histograms of CINR for different coverage combinations with a UDP downlink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas and PSCR MN, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

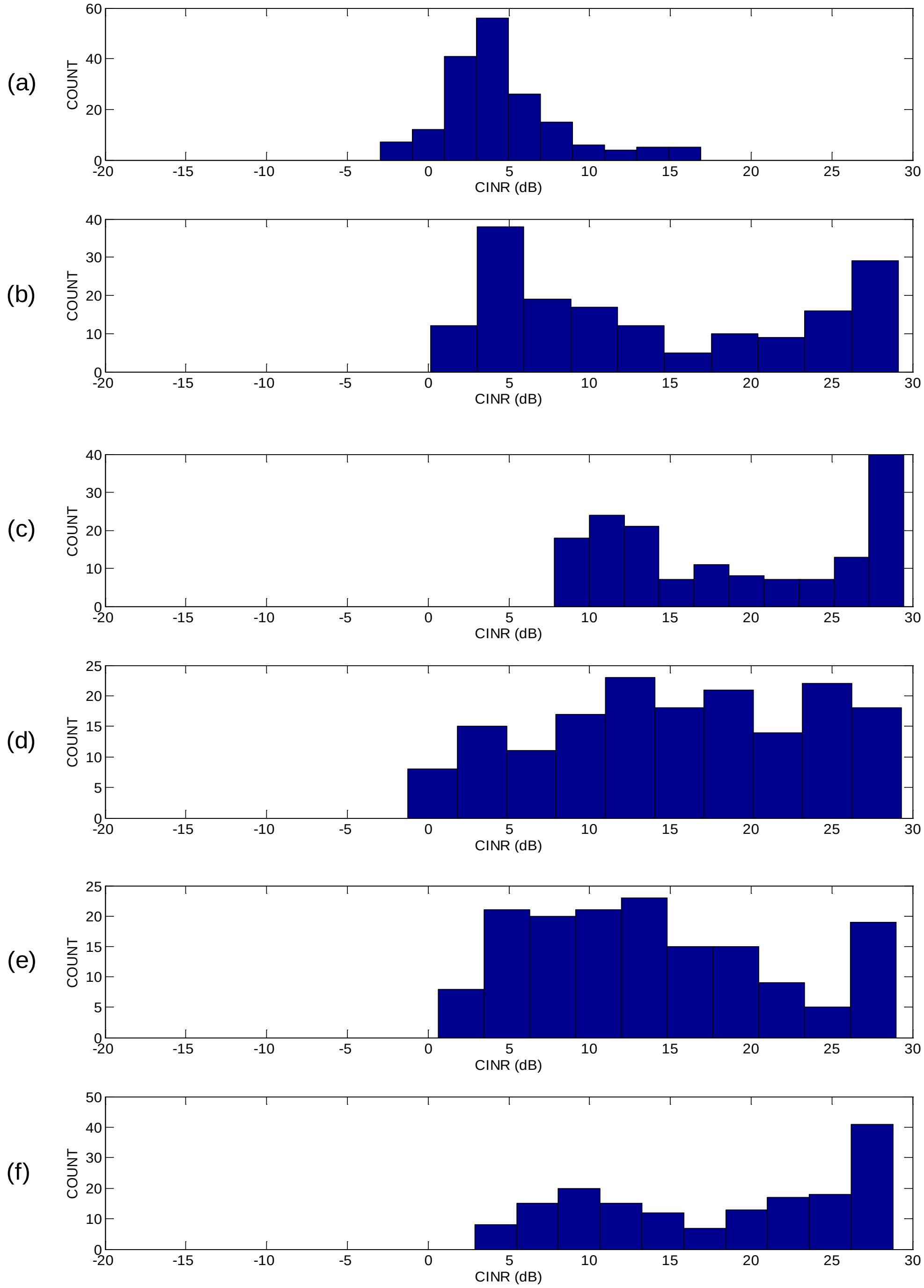

Figure 115. Level 2 histograms of CINR with different coverage combinations for a UDP uplink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas and PSCR MN, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

Table 55. Level 2 CINR statistics for a UDP downlink data flow.

Coverage Combination	**Mean CINR (dB)**	**Median CINR (dB)**	**Standard Deviation (dB)**	**Min CINR (dB)**	**Max CINR (dB)**
PSCR MN	2.8	1.8	3.9	-2.3	17.4
COW 8 W	11.2	10.3	9.1	-2.1	26.3
COW 40 W	16.0	14.5	6.9	5.2	27.4
SCDA 5 W+ PSCR MN	15.2	16.5	7.0	-0.2	26.8
SCDA 5 W + COW 8 W+ PSCR MN	11.9	11.3	6.6	-4.3	26.2
SCDA 5 W + COW 40 W + PSCR MN	16.7	18.8	6.4	3.3	25.9

Table 56. Level 2 CINR statistics for a UDP uplink data flow.

Coverage Combination	**Mean CINR (dB)**	**Median CINR (dB)**	**Standard Deviation (dB)**	**Min CINR (dB)**	**Max CINR (dB)**
PSCR MN	4.0	4.0	3.8	-3.0	16.9
COW 8 W	13.9	11.5	9.4	0.2	29.1
COW 40 W	19.1	17.9	7.5	7.8	29.5
SCDA 5 W+ PSCR MN	15.5	15.8	8.1	-1.2	29.3
SCDA 5 W + COW 8 W+ PSCR MN	13.9	12.6	7.7	0.6	29.0
SCDA 5 W + COW 40 W + PSCR MN	18.1	20.1	7.9	2.9	28.8

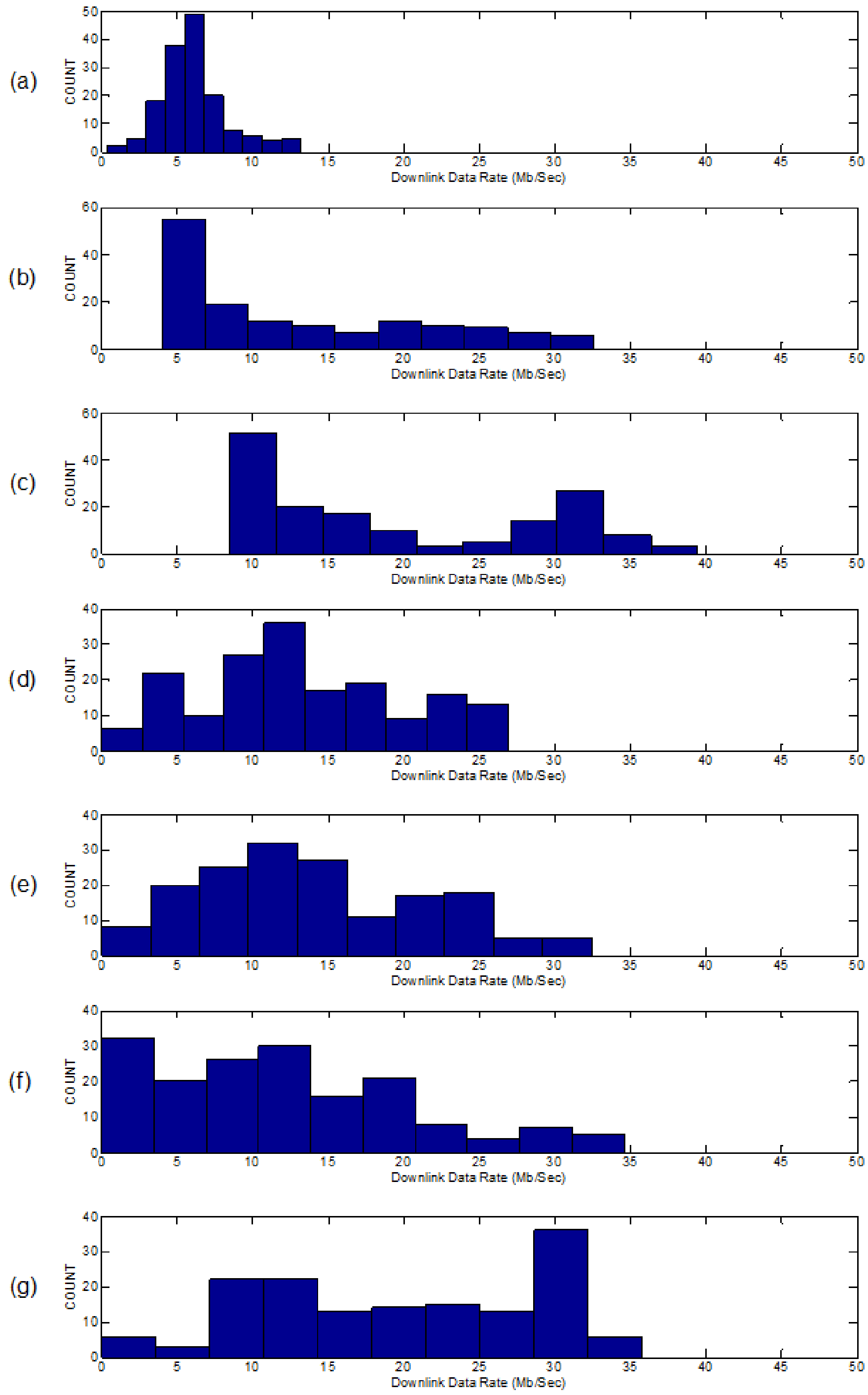

Figure 116. Level 2 histograms of PDSCH for different coverage combinations with a TCP downlink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas, (e) small cell at 5 W with discrete antennas and PSCR MN , (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (g) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

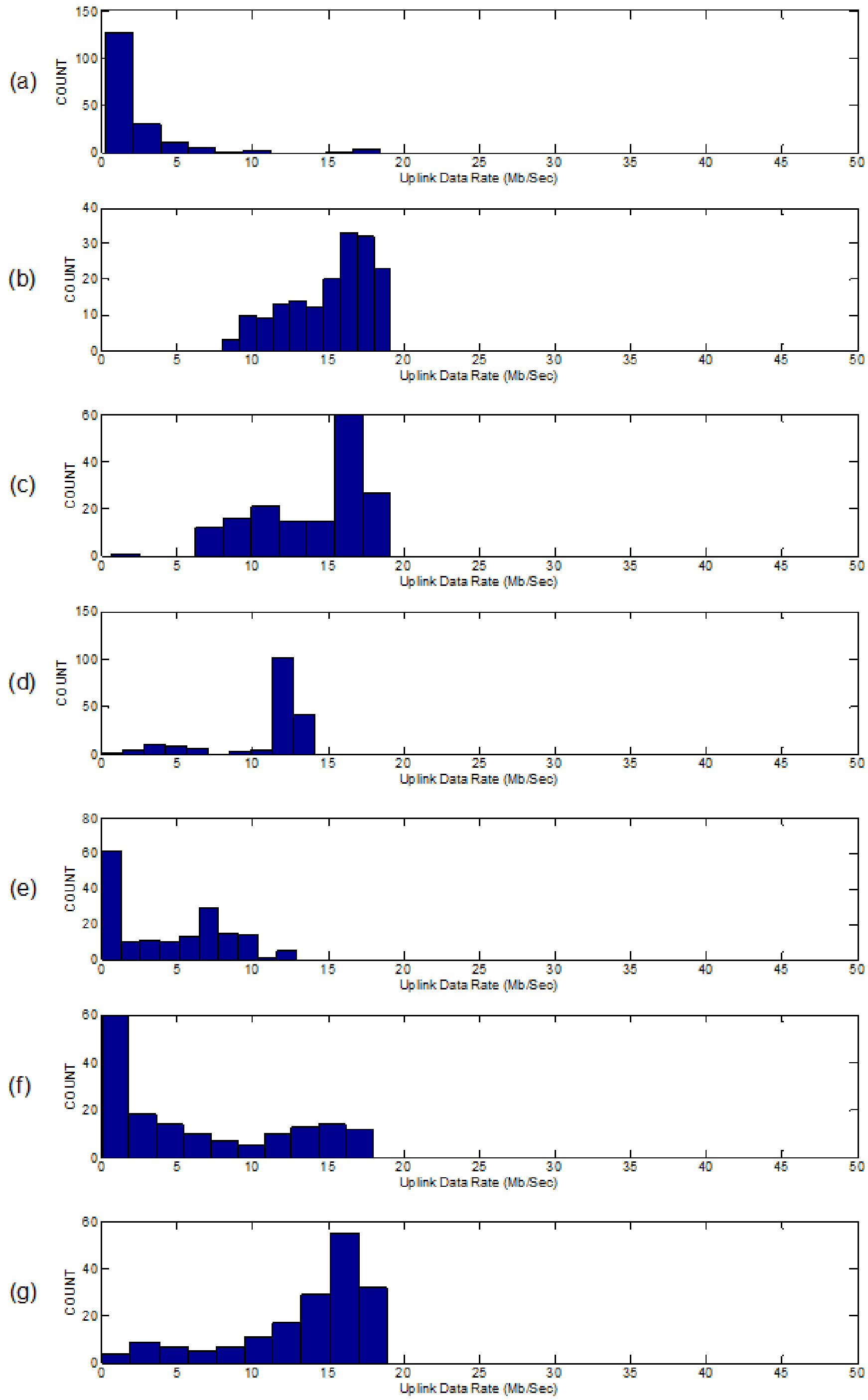

Figure 117. Level 2 histograms of PUSCH for different coverage combinations with a TCP uplink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas, (e) small cell at 5 W with discrete antennas and PSCR MN, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (g) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

Table 57. Level 2 PDSCH statistics for a TCP downlink data flow.

Coverage Combination	**Mean PDSCH (Mb/s)**	**Median PDSCH (Mb/s)**	**Standard Deviation (Mb/s)**	**Min PDSCH (Mb/s)**	**Max PDSCH (Mb/s)**
PSCR MN	6.1	5.8	2.3	0.4	13.2
COW 8 W	13.1	9.7	8.5	4.0	32.6
COW 40 W	19.5	15.6	9.4	8.5	39.4
SCDA 5 W	13.3	12.4	6.8	0.0	26.9
SCDA 5 W+ PSCR MN	13.9	12.8	7.4	0.0	32.4
SCDA 5 W + COW 8 W+ PSCR MN	12.0	10.8	8.6	0.0	34.6
SCDA 5 W + COW 40 W + PSCR MN	19.9	20.4	9.4	0.0	35.8

Table 58. Level 2 PUSCH statistics for a TCP uplink data flow.

Coverage Combination	**Mean PUSCH (Mb/s)**	**Median PUSCH (Mb/s)**	**Standard Deviation (Mb/s)**	**Min PUSCH (Mb/s)**	**Max PUSCH (Mb/s)**
PSCR MN	2.3	1.4	3.1	0.3	18.4
COW 8 W	15.1	15.9	2.8	8.0	19.1
COW 40 W	14.0	15.6	3.6	0.7	19.1
SCDA 5 W	11.0	12.2	3.1	0.0	14.1
SCDA 5 W+ PSCR MN	4.5	4.3	3.6	0.0	12.9
SCDA 5 W + COW 8 W+ PSCR MN	6.4	3.8	5.9	0.0	17.9
SCDA 5 W + COW 40 W + PSCR MN	13.3	15.0	4.6	0.0	18.9

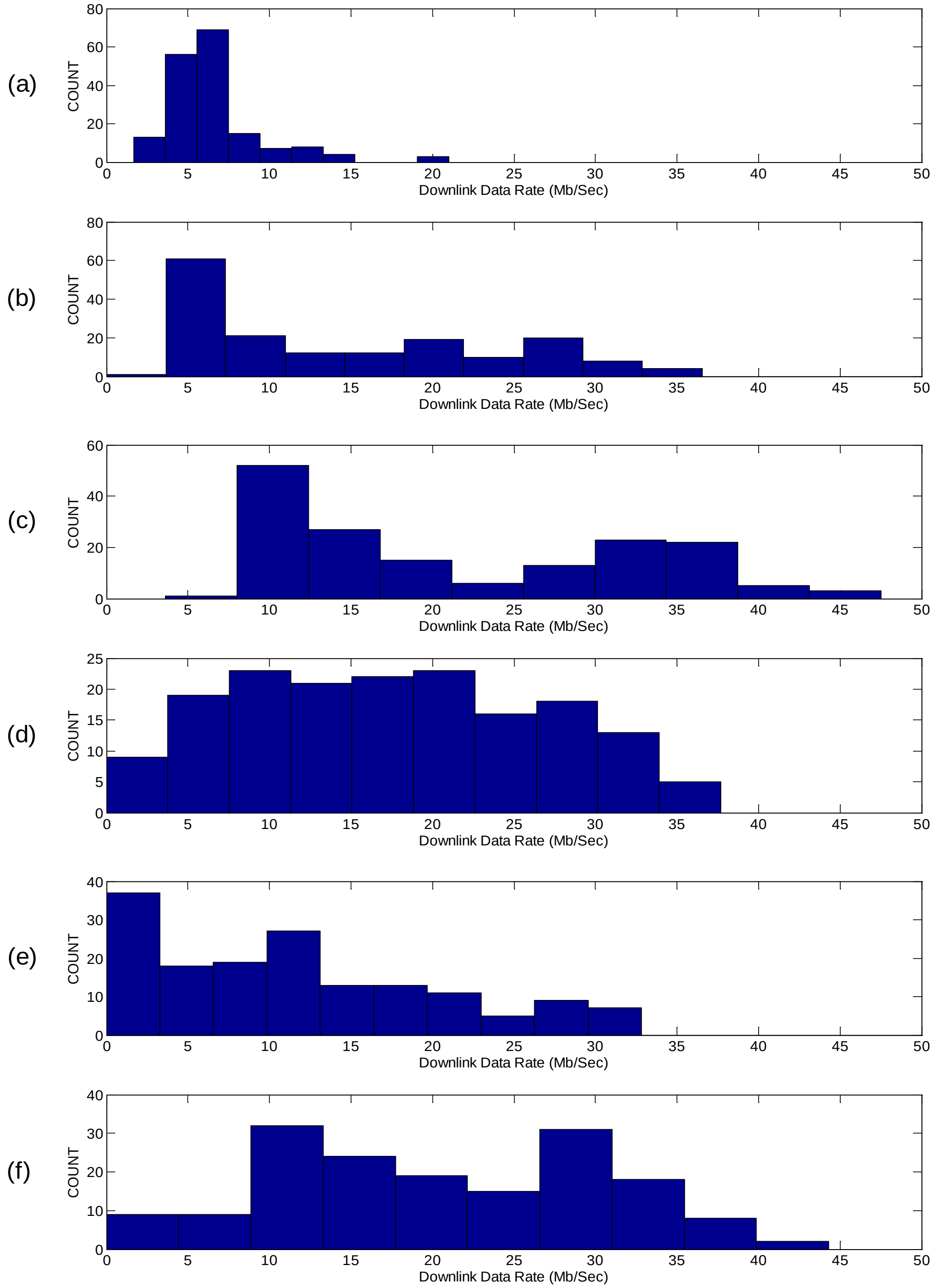

Figure 118. Level 2 histograms of PDSCH for different coverage combinations with a UDP downlink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas and PSCR MN, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

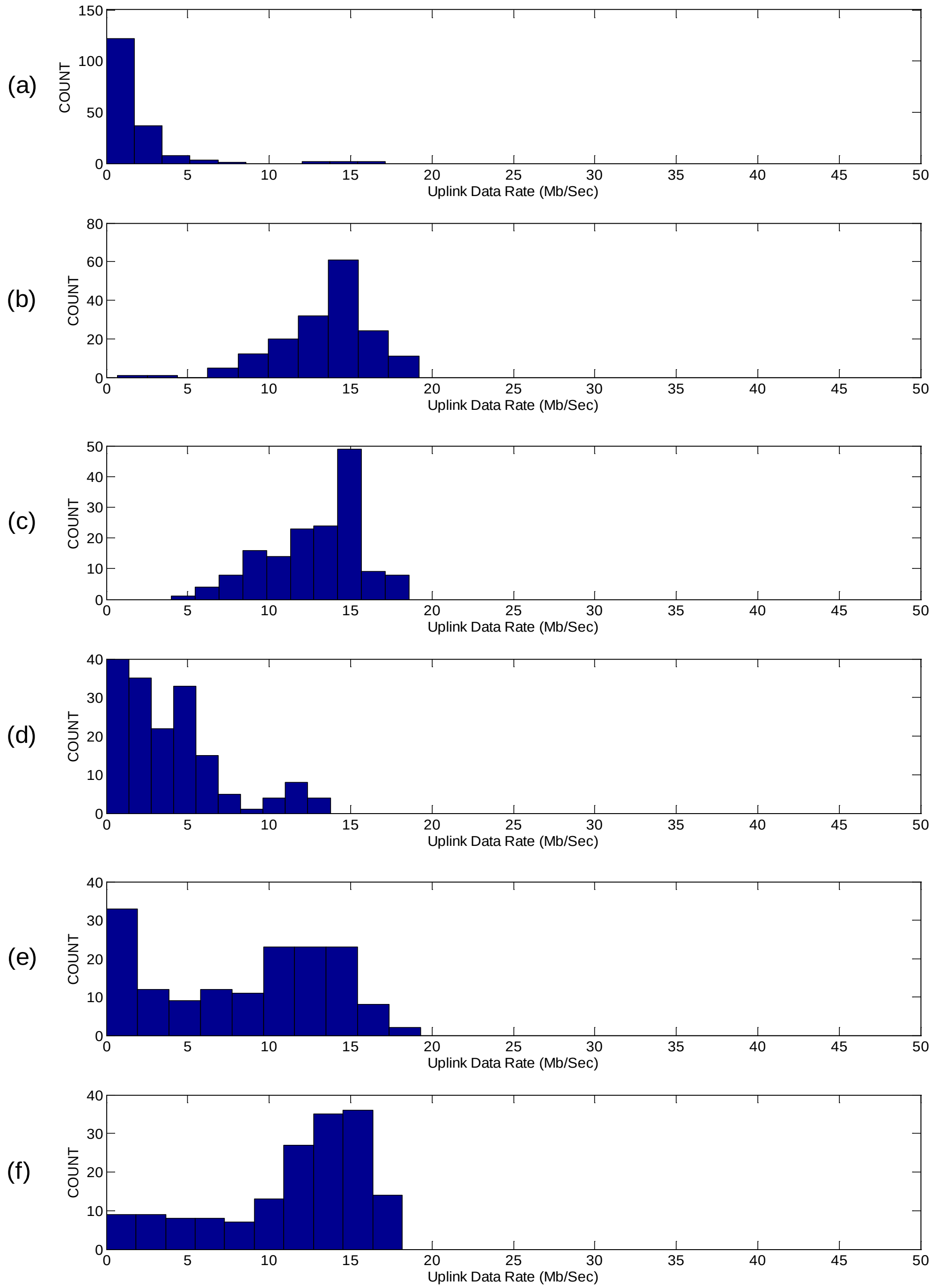

Figure 119. Level 2 histograms of PUSCH for different coverage combinations with a UDP uplink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas and PSCR MN, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

Table 59. Level 2 PDSCH statistics for a UDP downlink data flow.

Coverage Combination	Mean PDSCH (Mb/s)	Median PDSCH (Mb/s)	Standard Deviation (Mb/s)	Min PDSCH (Mb/s)	Max PDSCH (Mb/s)
PSCR MN	6.7	6.0	3.0	1.7	21.0
COW 8 W	14.4	11.0	9.2	0.0	36.5
COW 40 W	21.6	17.2	10.6	3.6	47.5
SCDA 5 W+ PSCR MN	17.5	17.2	9.1	0.0	37.7
SCDA 5 W + COW 8 W+ PSCR MN	12.3	11.1	9.0	0.0	32.8
SCDA 5 W + COW 40 W + PSCR MN	20.5	20.7	10.2	0.0	44.3

Table 60. Level 2 PDSCH statistics for a UDP uplink data flow.

Coverage Combination	Mean PDSCH (Mb/s)	Median PDSCH (Mb/s)	Standard Deviation (Mb/s)	Min PDSCH (Mb/s)	Max PDSCH (Mb/s)
PSCR MN	1.8	1.0	2.7	0.0	17.2
COW 8 W	13.5	14.1	2.8	0.7	19.2
COW 40 W	12.9	13.8	2.9	4.0	18.6
SCDA 5 W+ PSCR MN	4.0	3.3	3.2	0.0	13.8
SCDA 5 W + COW 8 W+ PSCR MN	8.5	9.8	5.5	0.0	19.3
SCDA 5 W + COW 40 W + PSCR MN	11.5	13.0	4.7	0.0	18.2

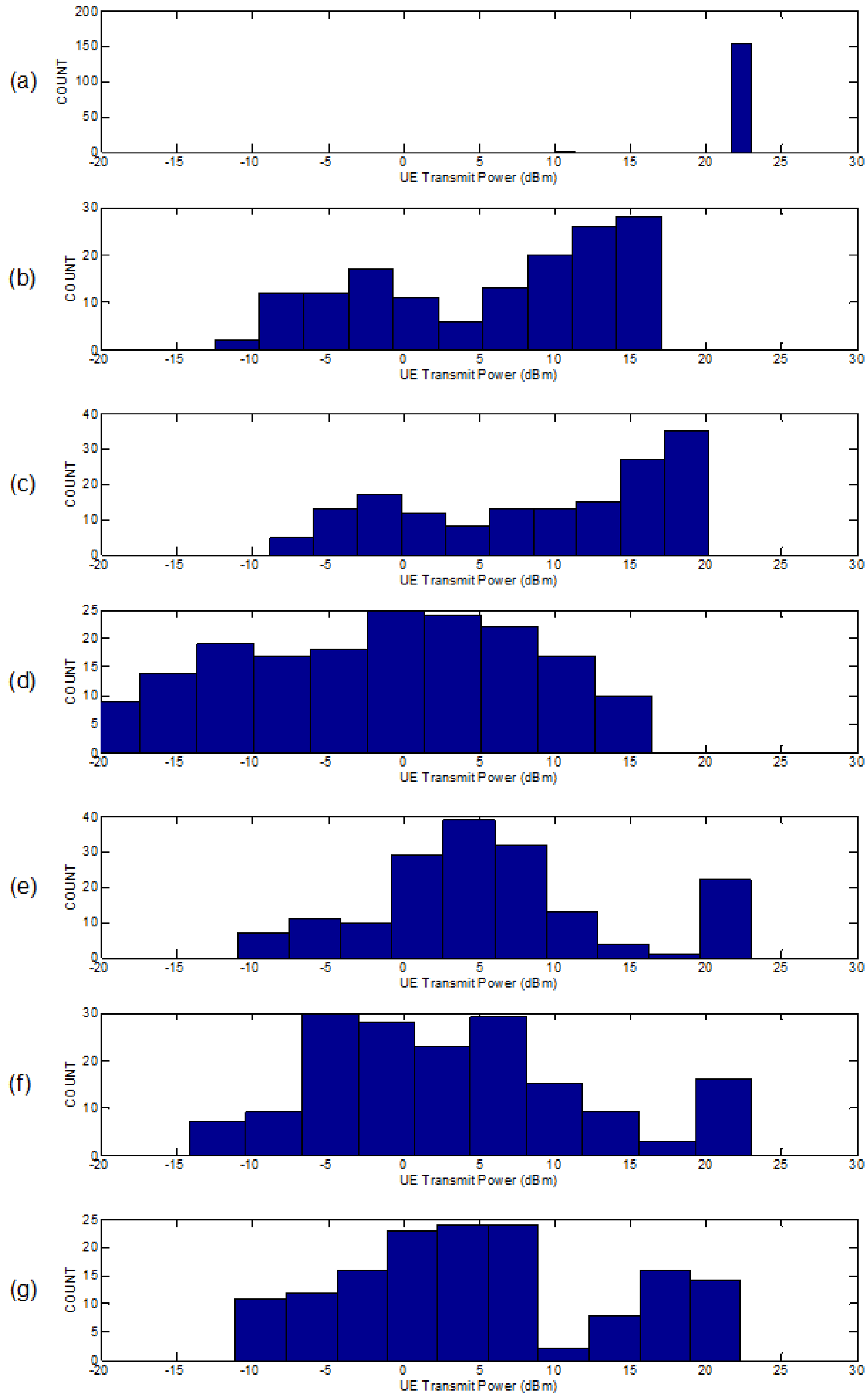

Figure 120. Level 2 histograms of UE transmit power for different coverage combinations with a TCP downlink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas, (e) small cell at 5 W with discrete antennas and PSCR MN, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (g) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

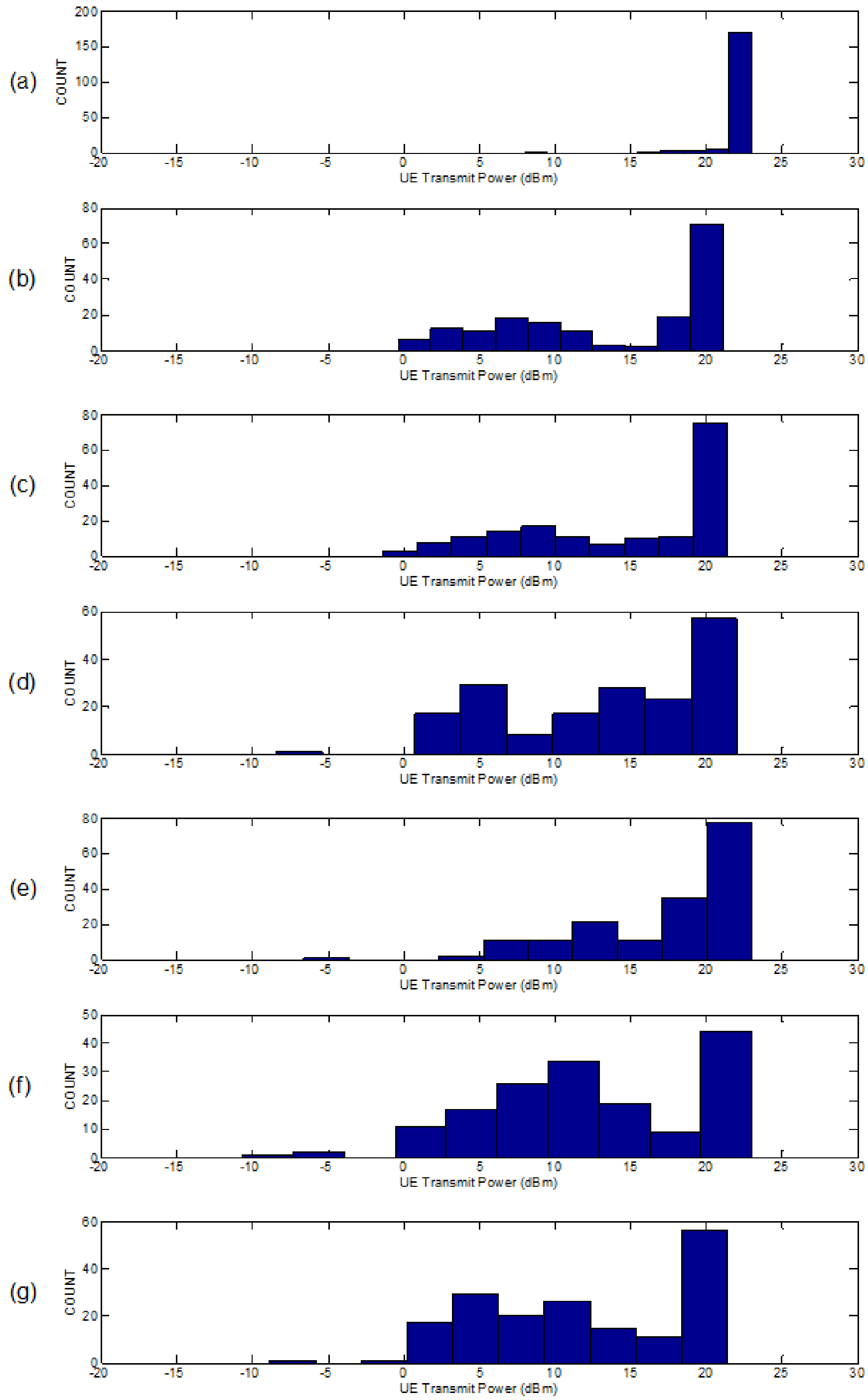

Figure 121. Level 2 histograms of UE transmit power for different coverage combinations with a TCP uplink data flow. (a) PSCR MN (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas, (e) small cell at 5 W with discrete antennas and PSCR MN, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (g) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

Table 61. Level 2 UE transmit power statistics for a TCP downlink data flow.

Coverage Combination	Mean UEtpwr (dBm)	Median UEtpwr (dBm)	Standard Deviation (dBm)	Min UEtpwr (dBm)	Max UEtpwr (dBm)
PSCR MN	22.7	23.0	1.1	10.1	23.0
COW 8 W	6.0	8.5	8.2	-12.5	17.1
COW 40 W	9.0	11.0	8.5	-8.9	20.2
SCDA 5 W	-1.6	-0.7	9.6	-21.2	16.4
SCDA 5 W+ PSCR MN	5.9	4.6	8.4	-11	23
SCDA 5 W + COW 8 W+ PSCR MN	3.4	2.3	9.2	-14.2	23
SCDA 5 W + COW 40 W + PSCR MN	5.0	3.5	9.0	-11.1	22.3

Table 62. Level 2 UE transmit power statistics for a TCP uplink data flow.

Coverage Combination	Mean UEtpwr (dBm)	Median UEtpwr (dBm)	Standard Deviation (dBm)	Min UEtpwr (dBm)	Max UEtpwr (dBm)
PSCR MN	22.1	22.2	1.3	8.0	23
COW 8 W	14.1	17.4	7.0	-0.4	21.1
COW 40 W	14.5	17.3	6.9	-1.4	21.4
SCDA 5 W	13.7	15.1	6.9	-8.4	22.1
SCDA 5 W+ PSCR MN	17.5	19.4	5.4	-6.6	23.0
SCDA 5 W + COW 8 W+ PSCR MN	12.6	12.0	7.3	-10.7	23.0
SCDA 5 W + COW 40 W + PSCR MN	12.0	10.8	7.1	-8.9	21.4

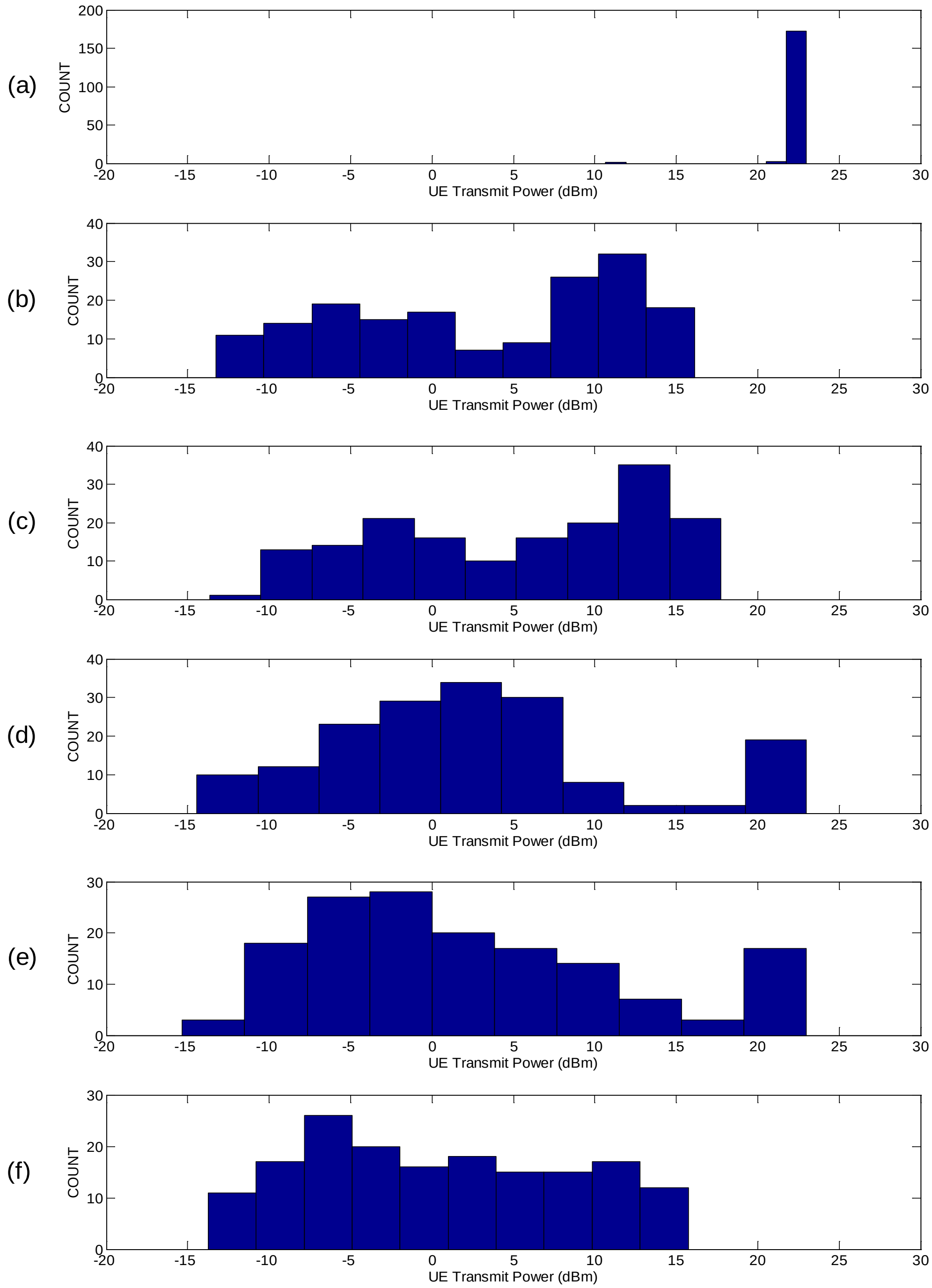

Figure 122. Level 2 histograms of UE transmit power for different coverage combinations with a UDP downlink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas and PSCR MN, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

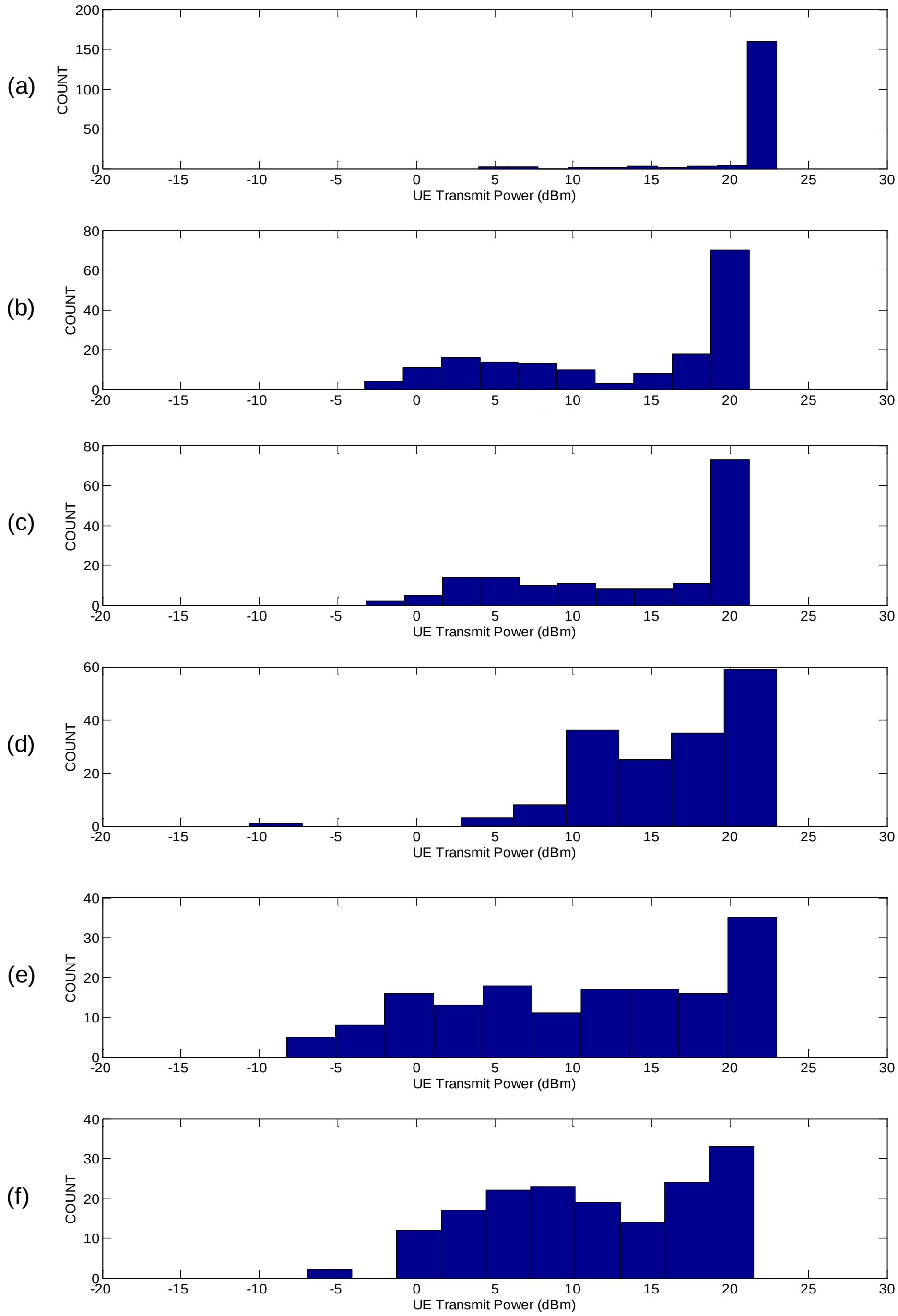

Figure 123. Level 2 histograms of UE transmit power for different coverage combinations with a UDP uplink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas and PSCR MN, (e) small cell at 5 W with discrete antennas and PSCR MN and COW at 8 W, (f) small cell at 5 W with discrete antennas and PSCR MN and COW at 40 W.

Table 63. Level 2 UE transmit power statistics for a UDP downlink data flow.

Coverage Combination	Mean UEtpwr (dBm)	Median UEtpwr (dBm)	Standard Deviation (dBm)	Min UEtpwr (dBm)	Max UEtpwr (dBm)
PSCR MN	22.8	23.0	1.0	10.7	23.0
COW 8 W	3.2	4.6	8.7	-13.3	16.1
COW 40 W	5.4	6.8	8.3	-13.6	17.7
SCDA 5 W+ PSCR MN	2.6	1.5	9.4	-14.4	23.0
SCDA 5 W + COW 8 W+ PSCR MN	2.4	-0.1	9.9	-15.3	23.0
SCDA 5 W + COW 40 W + PSCR MN	0.4	-0.5	8.0	-13.8	15.7

Table 64. Level 2 UE transmit power statistics for a UDP uplink data flow.

Coverage Combination	Mean UEtpwr (dBm)	Median UEtpwr (dBm)	Standard Deviation (dBm)	Min UEtpwr (dBm)	Max UEtpwr (dBm)
PSCR MN	21.7	22.3	3.0	4.0	23.0
COW 8 W	13.3	16.9	7.7	-3.3	23.0
COW 40 W	14.2	18.2	7.2	-3.2	21.2
SCDA 5 W+ PSCR MN	16.4	17.1	5.2	-10.6	23.0
SCDA 5 W + COW 8 W+ PSCR MN	10.8	11.4	8.8	-8.3	23.0
SCDA 5 W + COW 40 W + PSCR MN	11.4	11.2	6.8	-6.9	21.5

3.5 DLC Outdoor Ground Level Measured Results

The outdoor walk test covers the outside perimeter of the DLC on the ground (street) level. The route begins on the north side of the DLC, on the sidewalk outside the Digital Energy Lab, and it progresses in a clockwise direction around the DLC and back to the start point. We collected data for both uplink and downlink data flows using both TCP and UDP.

Results were obtained on the outside permiter of the DLC for the five coverage combinations:

- PSCR MN only
- SCDA only at 5 W input (TCP only)
- COW only at 8 W
- COW only at 40 W
- PSCR MN + SCDA at 5 W (TCP only)

Figures 124–128 show maps of the serving cell RSRP as a function of coverage for a TCP downlink data flow. The corresponding RSRP histograms are plotted in Figures 129–132, and statistical summaries are given in Tables 65–68. When the PSCR MN is the source of coverage, the resulting RSRP signal levels outside are approximately 5 dB stronger than those on level 2 and approximately 12 dB stronger than the level 1 values. This trend is attributed to the combination of improved macro network coverage on the higher levels of the DLC and the electromagnetic shielding provided by the building materials. The biggest increases in RSRP levels are seen when the COW is active, and this occurs on the east side of the DLC where the COW is located. The weakest signal levels are observed on the west and northwest side of the DLC, due to RF transmission blockage effects of DLC structure.

Figure 127 shows the RSRP for the SCDA system transmitting at 5 W, and there is significant leakage from a window in the Digital Energy Lab located on the north side of the DLC. The small cell leakage drops off significantly on the south side of the DLC due to building blockage effects. This drop off effect lessens when the SCDA system and the PSCR MN are both active—the macro network provides improved coverage on the south side of the DLC.

The histograms of the CINR are shown in Figures 133–136. Summary statistical results are provided in Tables 69–72. When the PSCR MN is the sole source of coverage the outdoor CINR levels are typically 3 dB better than the corresponding results on level 2, and 10 dB better than those on level 1. Major improvements in CINR levels are seen when the COW is transmitting at either 8 W or 40 W. The SCDA system provides high CINR levels on the north side of the DLC, but poor results are obtained on the south side due to building blockage effects.

The PDSCH downlink data rate results are shown in Figures 137 and 139 for TCP and UDP respectively. Statistical summaries are provided in Tables 73 and 75. Typical data rates in the range of 5–10 Mb/s are seen with coverage provided by the PSCR MN. When the COW is operating at either power level, the maximum data rates approach 40 Mb/s for TCP and 50 Mb/s for UDP. High data rates approaching 30 Mb/s occur on the north side of the DLC but drop off to low rates on the south side of the DLC due to low signal levels.

The PUSCH uplink data rates for TCP and UDP are depicted in Figures 138 and 140 respectively. Statistical summaries are provided in Tables 74 and 76. Maximum uplink data rates exceed 5 Mb/s for TCP and 10 Mb/s for UDP. The lowest data rates are seen on the north side of the DLC, where the PSCR MN coverage is weakest. When the COW is active, the overall data rates improve with maximum values approaching 20 Mb/s. High uplink data rates in the range of 10–15 Mb/s are seen over most of the path, but low rates occur on the south side of the DLC due to high path losses. When both the SCDA and the PSCR MN are active, system performance drops off noticeably with a high count of low data rates—this is due to handovers between the SCDA and the macro network. This could be remedied by careful network optimization.

The UE transmit power levels for both downlink and uplink data flows for both TCP and UDP are shown in Figures 141–144. The associated statistics are given in Tables 77–80. The greatest stress on the UE occurs when the PSCR MN provides coverage. This is due to the high path losses between the UE and the Green Mountain eNB. The situation improves significantly when the COW provides coverage, and the UE power levels are significantly lower. The SCDA also provides a reduction in UE transmit power levels over most of the walk path, although higher power levels are required on the south side of the DLC due to the RF blockage of the Engineering Center. The situation is not nearly as good when both the SCDA and PSCR MN provide coverage. This is caused by handovers to the PSCR network which increase the UE transmit power levels. The uplink transmit power levels once again are typically higher than the downlink results due to a heavier data payload.

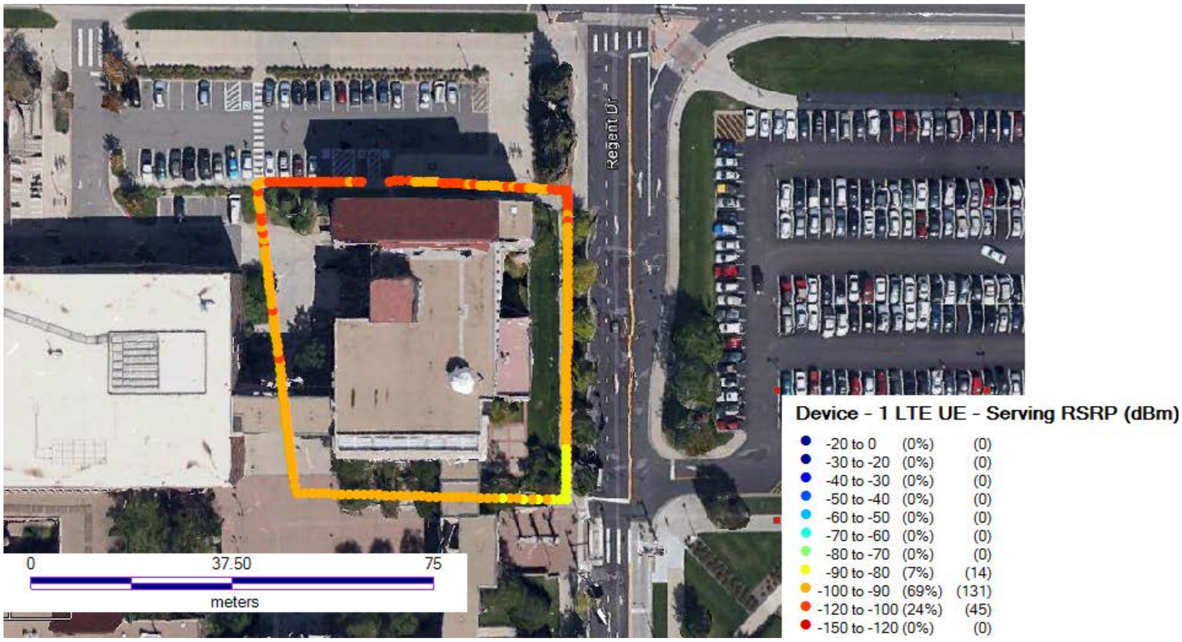

Figure 124. Outside ground level reference signal received power (RSRP) for a TCP downlink data flow with the PSCR MN. North is at the top of the figure.

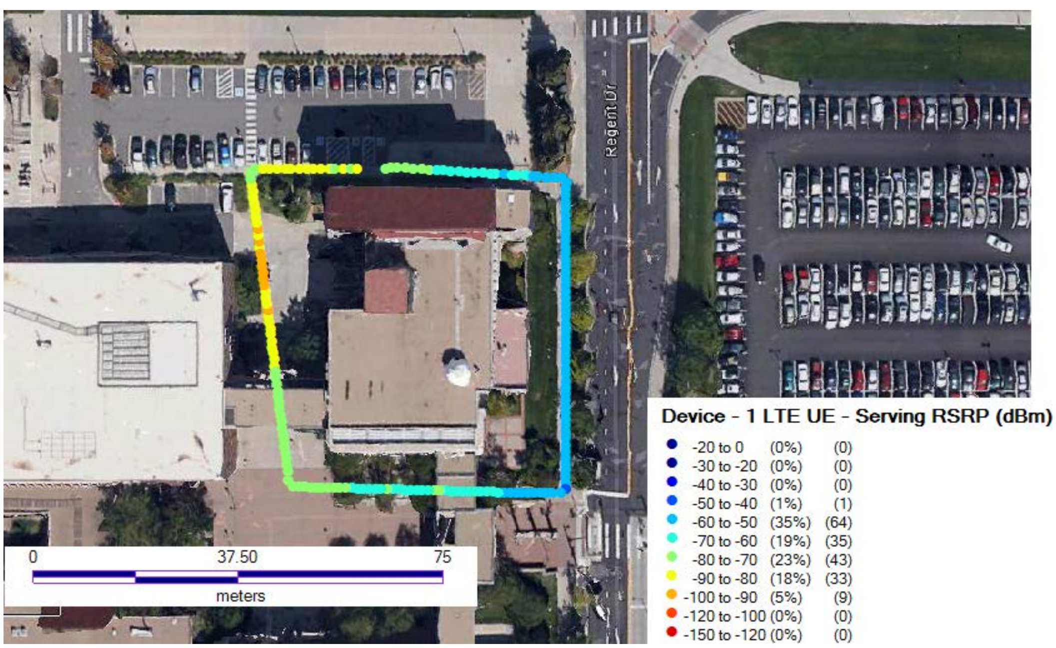

Figure 125. Outside ground level reference signal received power (RSRP) for a TCP downlink data flow with a COW at 8 W. North is at the top of the figure.

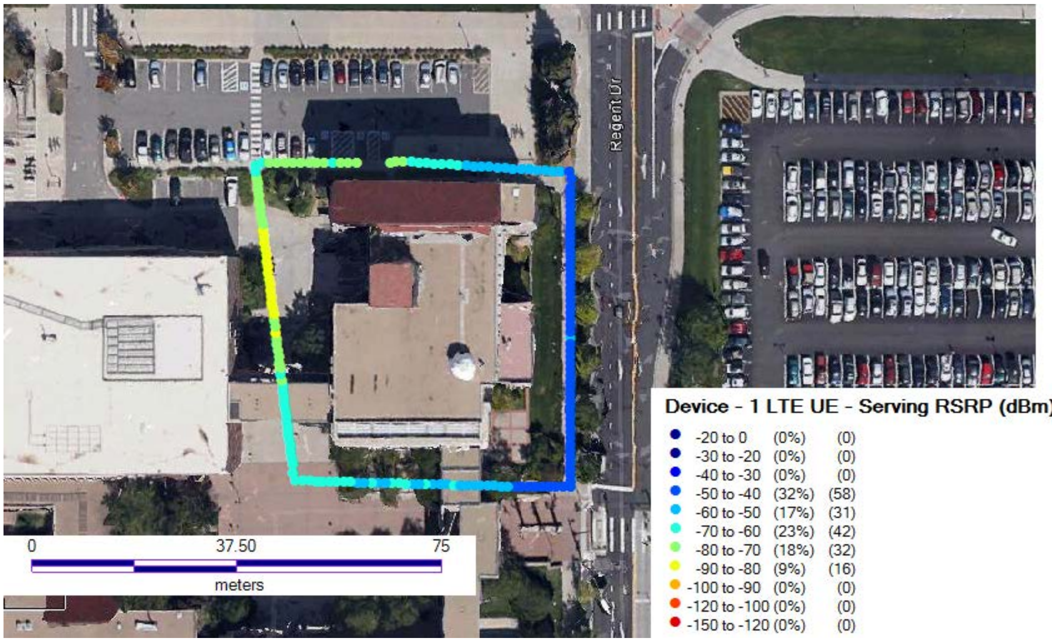

Figure 126. Outside ground level reference signal received power (RSRP) for a TCP downlink data flow with the COW at 40 W. North is at the top of the figure.

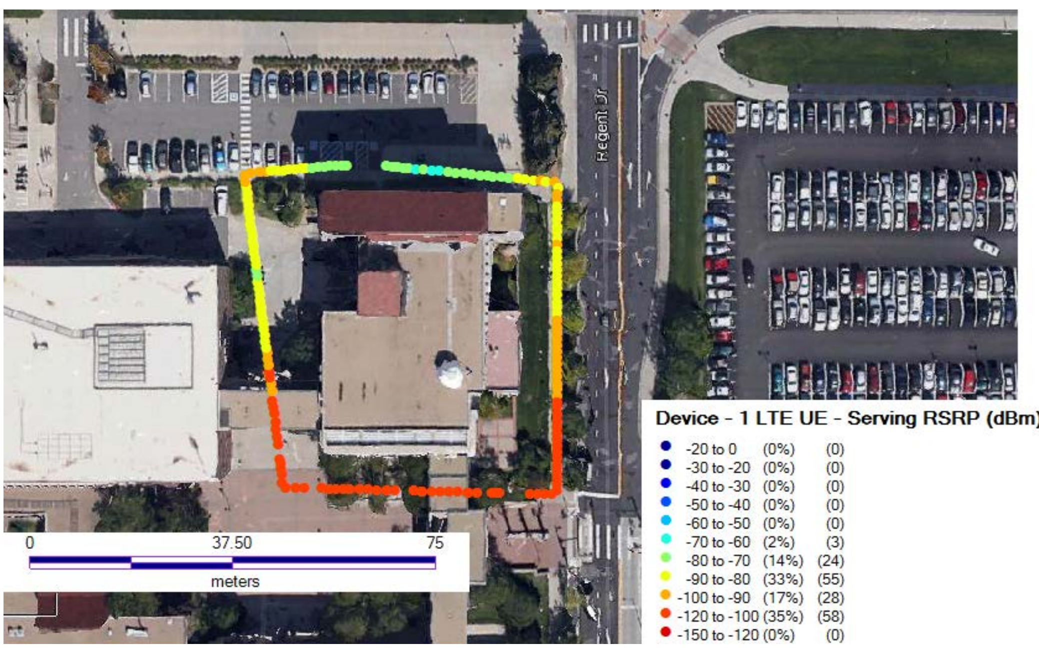

Figure 127. Outside reference signal received power (RSRP) for a TCP downlink data flow with a small cell at 5 W and discrete antennas. North is at the top of the figure.

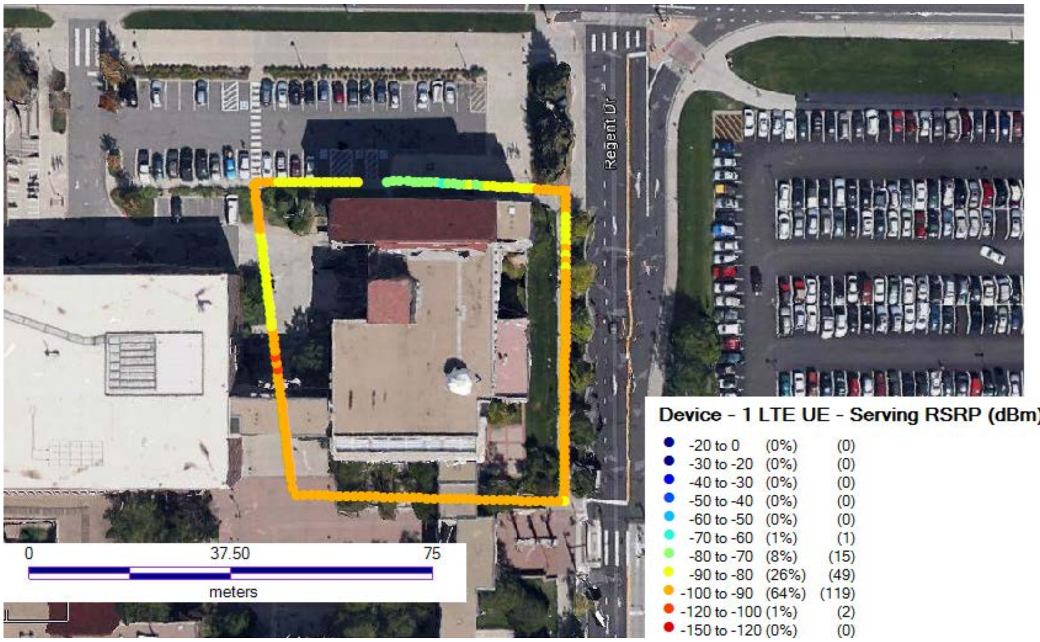

Figure 128. Outside reference signal received power (RSRP) for a TCP downlink data flow with a small cell at 5 W and discrete antennas and the PSCR MN. North is at the top of the figure.

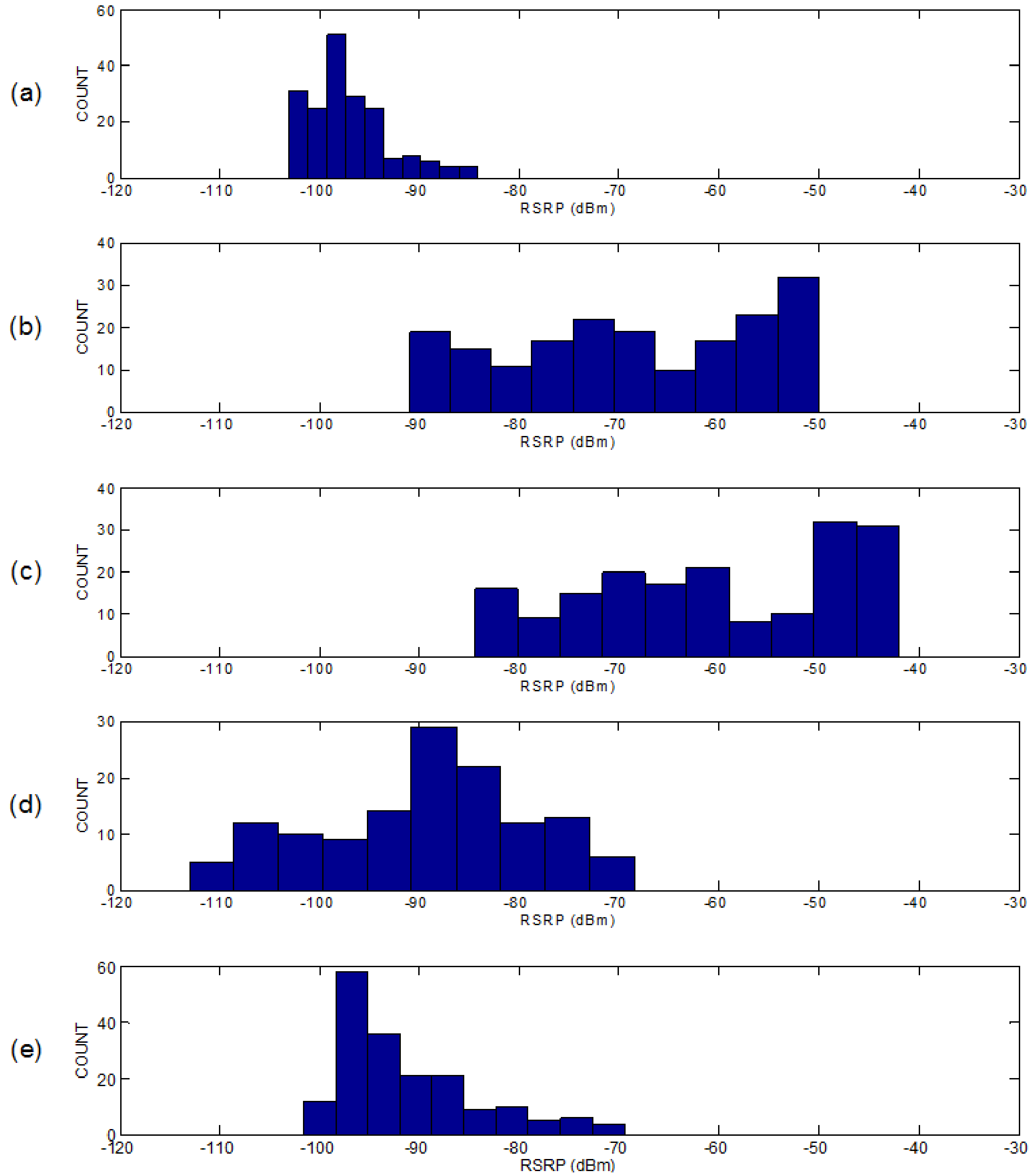

Figure 129. Outside ground level histograms of RSRP for different coverage combinations with a TCP downlink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas, (e) small cell at 5 W with discrete antennas and PSCR MN.

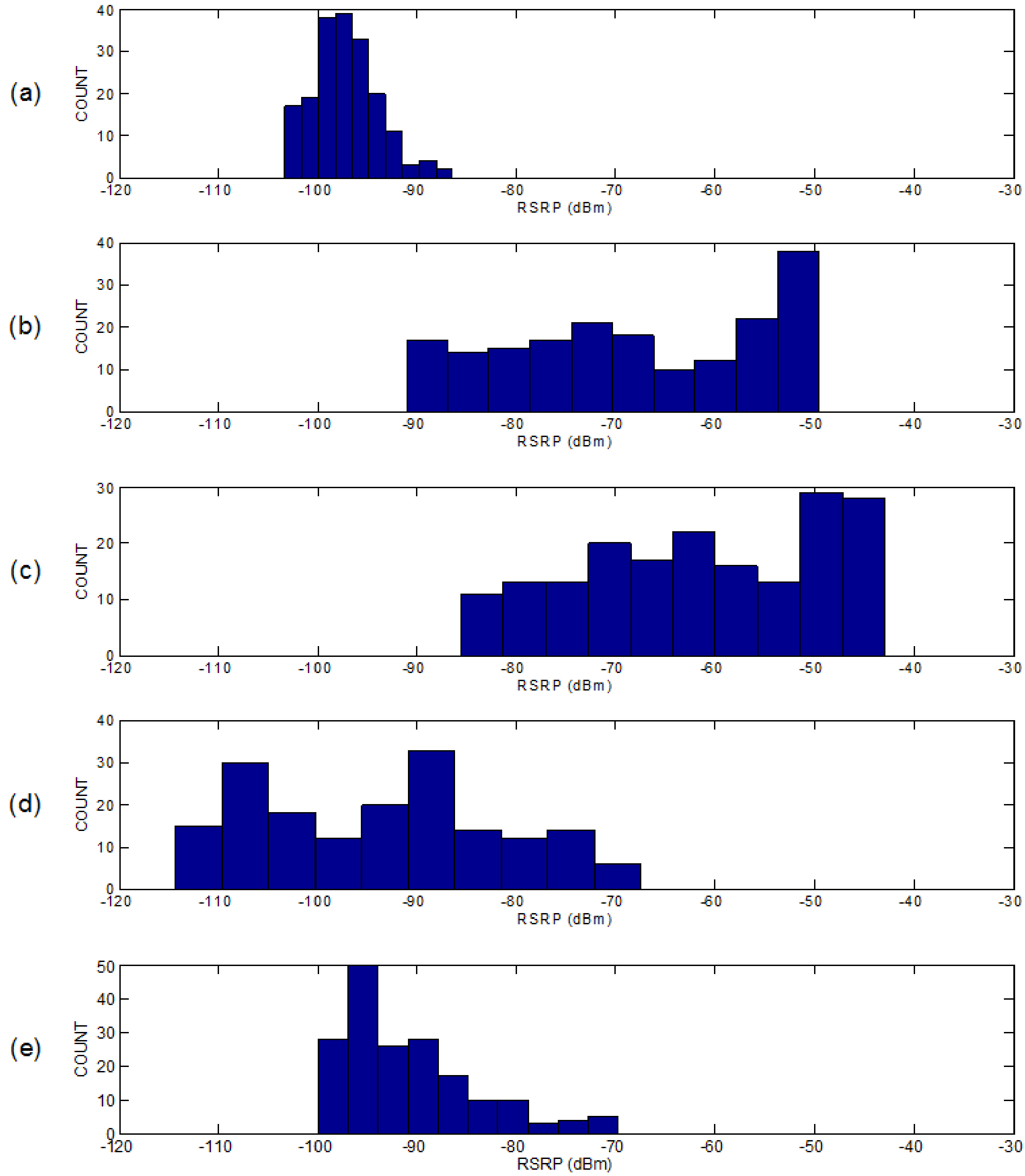

Figure 130. Outside ground level histograms of RSRP for different coverage combinations with a TCP uplink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas, (e) small cell at 5 W with discrete antennas and the PSCR MN.

Table 65. Outside ground level RSRP statistics for a TCP downlink data flow.

Coverage Combination	**Mean RSRP (dBm)**	**Median RSRP (dBm)**	**Standard Deviation (dBm)**	**Min RSRP (dBm)**	**Max RSRP (dBm)**
PSCR MN	-97.0	-97.7	4.0	-103.0	-84.2
COW 8 W	-68.5	-67.6	12.4	-91.0	-50.0
COW 40 W	-60.5	-60.8	12.7	-84.4	-42.0
SCDA 5 W	-89.5	-88.2	10.7	-113.0	-68.5
SCDA 5 W + COW 40 W + PSCR MN	-91.1	-93.6	7.0	-101.6	-69.5

Table 66. Outside ground level RSRP statistics for a TCP uplink data flow.

Coverage Combination	**Mean RSRP (dBm)**	**Median RSRP (dBm)**	**Standard Deviation (dBm)**	**Min RSRP (dBm)**	**Max RSRP (dBm)**
PSCR MN	-97.2	-97.5	3.3	-103.2	-86.4
COW 8 W	-68.0	-68.2	12.8	-91.0	-49.6
COW 40 W	-61.1	-60.8	12.2	-85.6	-42.9
SCDA 5 W	-93.4	-91.8	12.0	-114.3	-67.4
SCDA 5 W + COW 40 W + PSCR MN	-90.8	-92.4	6.8	-100.0	-69.8

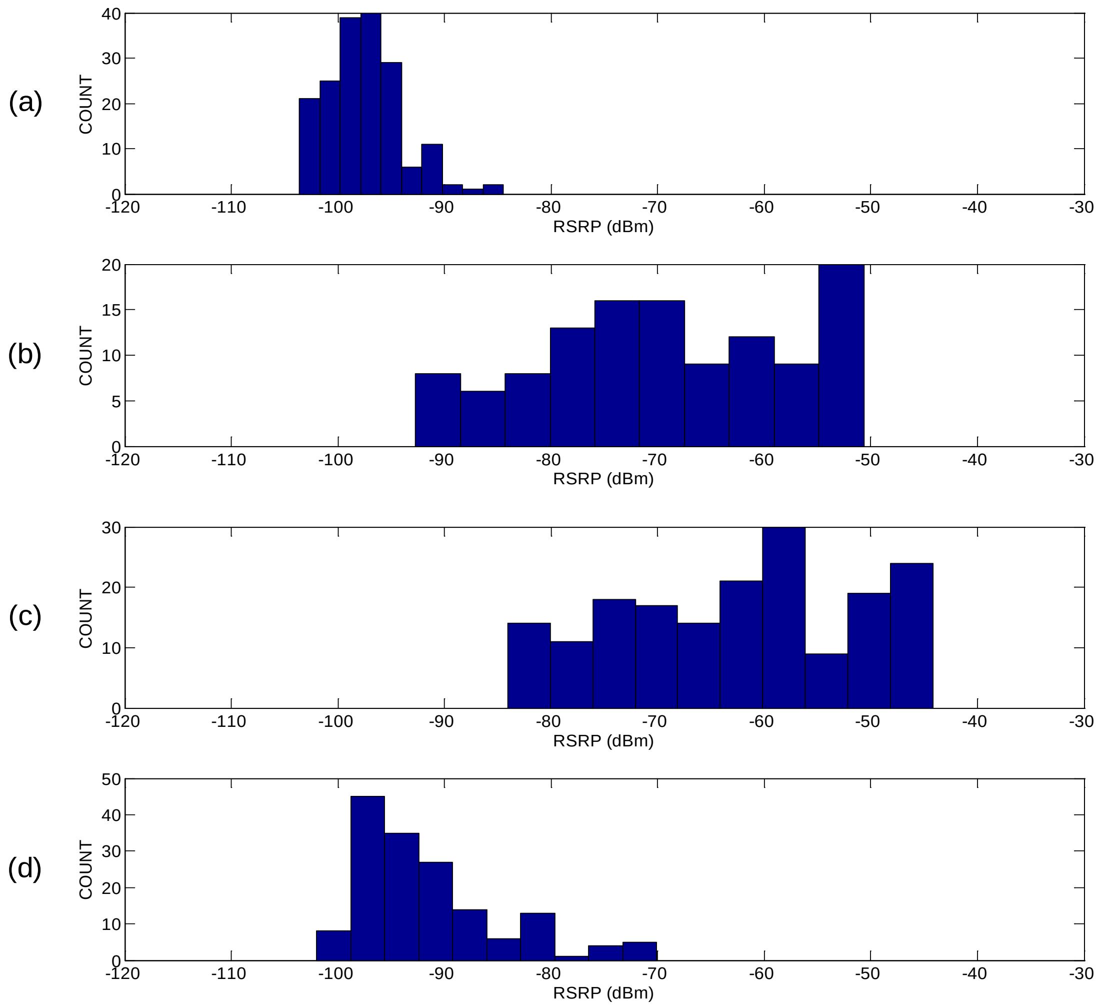

Figure 131. Outside ground level histograms of RSRP for different coverage combinations with a UDP downlink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas and the PSCR MN.

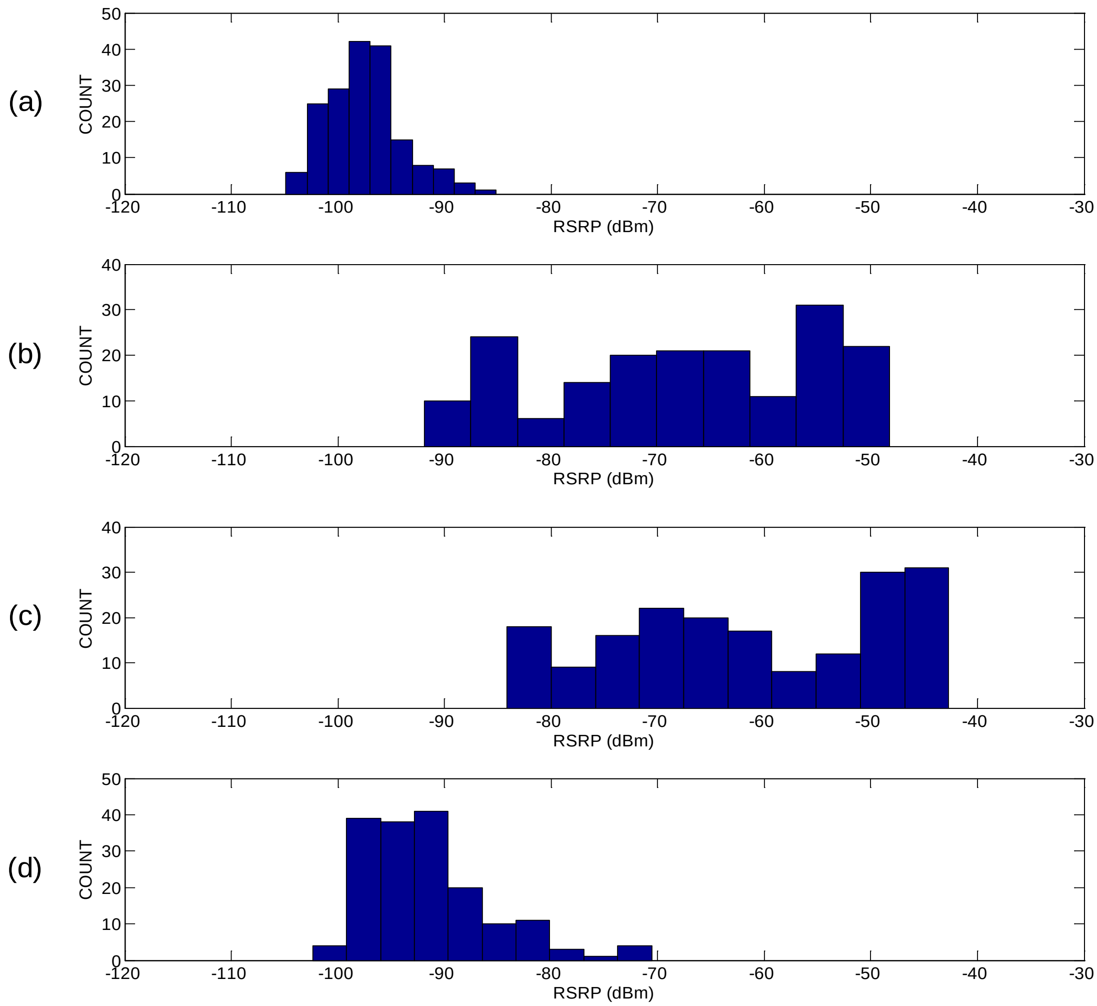

Figure 132. Outside ground level histograms of RSRP for different coverage options with a UDP uplink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas and the PSCR MN.

Table 67. Outside ground level RSRP statistics for a UDP downlink data flow.

Coverage Combination	**Mean RSRP (dBm)**	**Median RSRP (dBm)**	**Standard Deviation (dBm)**	**Min RSRP (dBm)**	**Max RSRP (dBm)**
PSCR MN	-97.5	-97.7	3.5	-103.6	-84.5
COW 8 W	-69.2	-69.1	11.7	-92.7	-50.7
COW 40 W	-62.6	-61.9	11.1	-84.1	-44.2
SCDA 5 W + PSCR MN	-91.4	-93.3	6.8	-102.0	-70.1

Table 68. Outside ground level RSRP statistics for a UDP uplink data flow.

Coverage Combination	**Mean RSRP (dBm)**	**Median RSRP (dBm)**	**Standard Deviation (dBm)**	**Min RSRP (dBm)**	**Max RSRP (dBm)**
PSCR MN	-97.4	-97.6	3.5	-104.9	-85.1
COW 8 W	-67.6	-66.9	12.4	-91.9	-48.3
COW 40 W	-61.1	-62.9	12.6	-84.1	-42.7
SCDA 5 W + PSCR MN	-91.5	-92.3	6.0	-102.4	-70.6

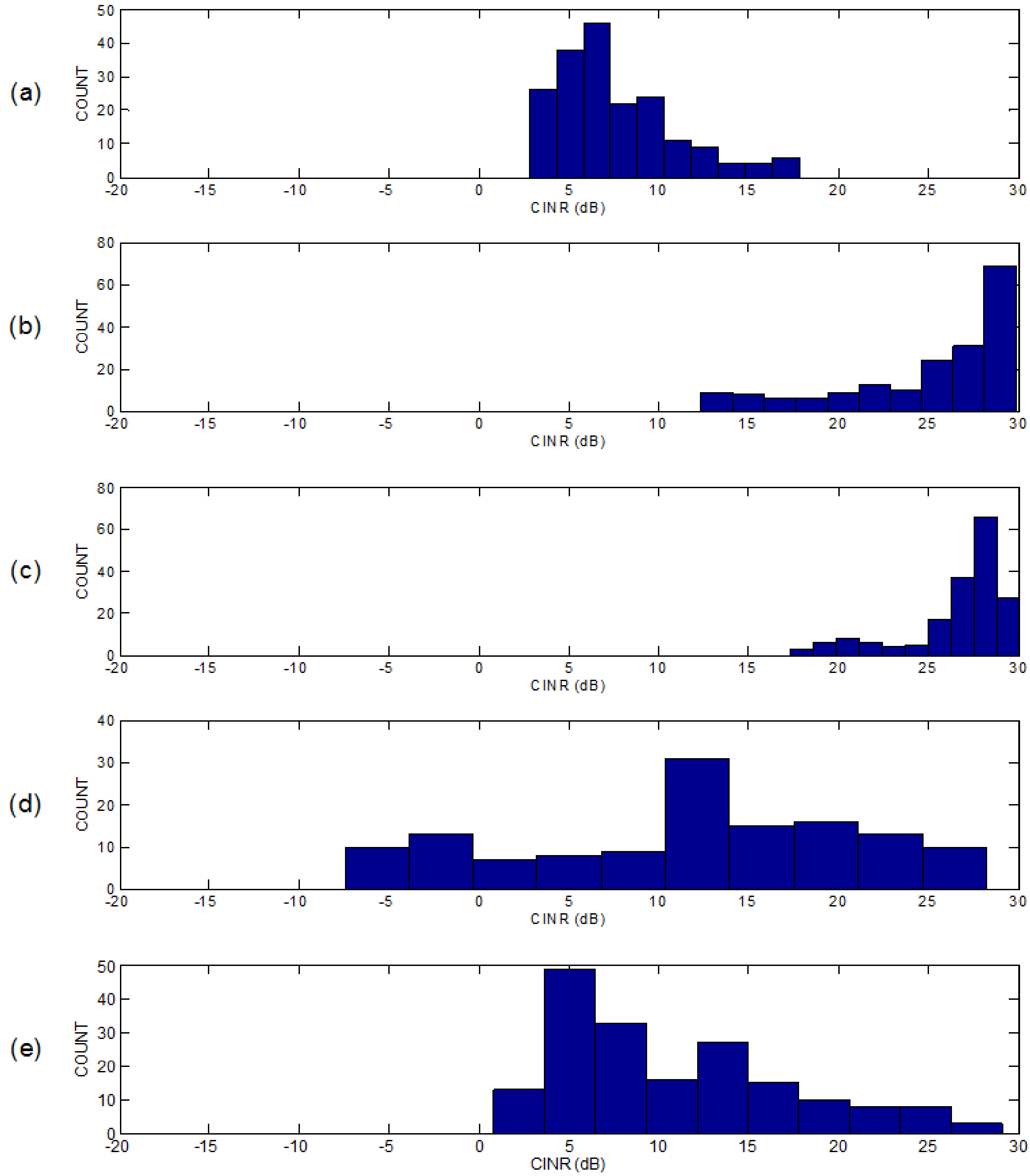

Figure 133. Outside ground level histograms of CINR for different coverage combinations with a TCP downlink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas, (e) small cell at 5 W with discrete antennas and the PSCR MN.

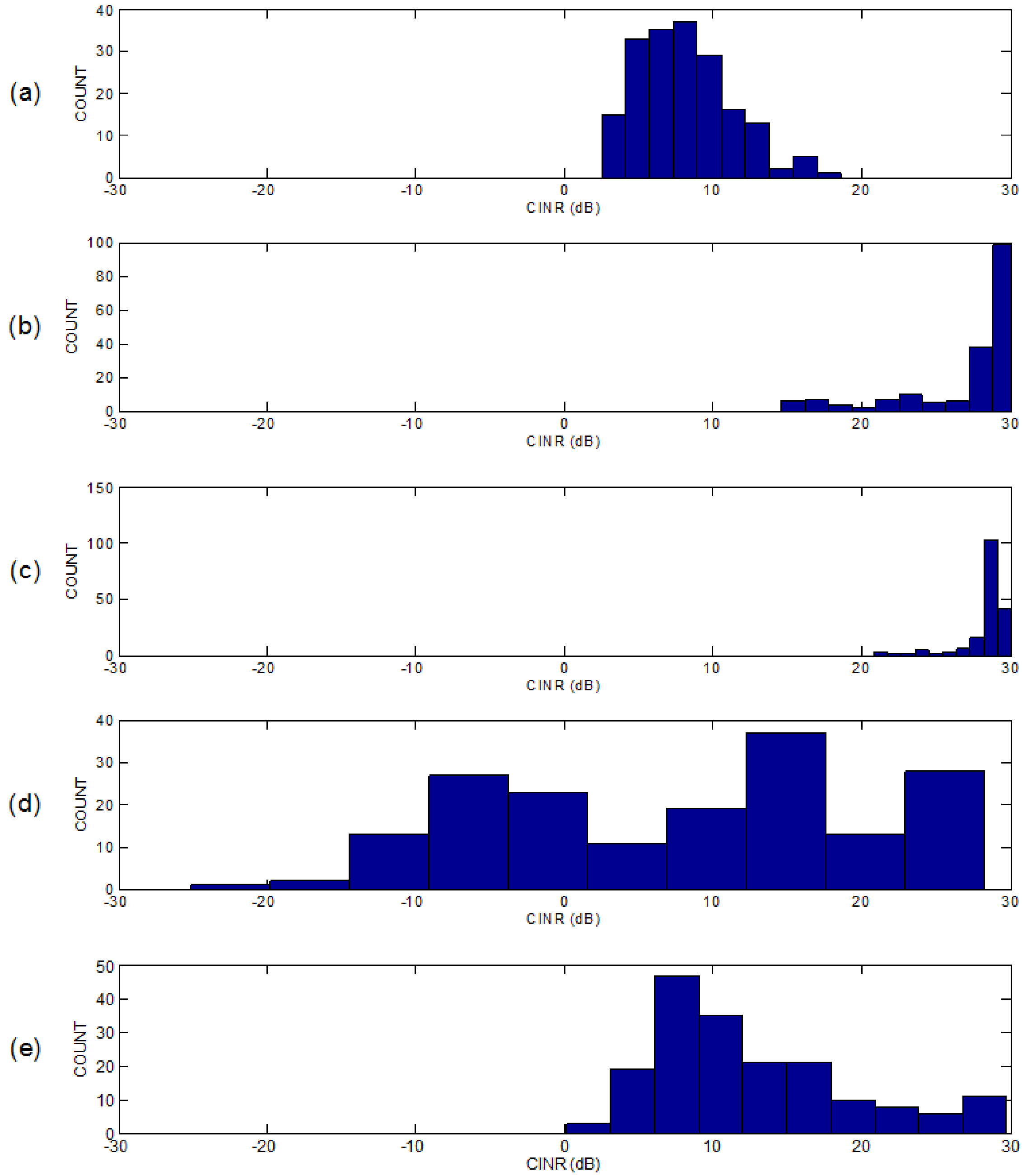

Figure 134. Outside ground level histograms of CINR for different coverage combinations with a TCP uplink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) +small cell at 5 W with discrete antennas, (e) small cell at 5 W with discrete antennas and PSCR MN.

Table 69. Outside ground level CINR statistics for a UDP downlink data flow.

Coverage Combination	**Mean CINR (dB)**	**Median CINR (dB)**	**Standard Deviation (dB)**	**Min CINR (dB)**	**Max CINR (dB)**
PSCR MN	7.6	6.8	3.3	2.8	17.8
COW 8 W	24.9	27.3	4.8	12.4	29.9
COW 40 W	26.6	27.6	2.9	17.3	30.1
SCDA 5 W	11.6	12.8	9.4	-7.5	28.2
SCDA 5 W + PSCR MN	10.9	9.0	6.3	0.8	29.1

Table 70. Outside ground level CINR statistics for a UDP uplink data flow.

Coverage Combination	**Mean CINR (dB)**	**Median CINR (dB)**	**Standard Deviation (dB)**	**Min CINR (dB)**	**Max CINR (dB)**
PSCR MN	8.1	7.7	3.1	2.5	18.6
COW 8 W	27.0	28.9	4.0	14.6	30.4
COW 40 W	28.4	28.9	1.7	20.8	30.1
SCDA 5 W	7.9	10.2	12.6	-25.1	28.3
SCDA 5 W + PSCR MN	12.5	10.5	6.8	0.2	29.8

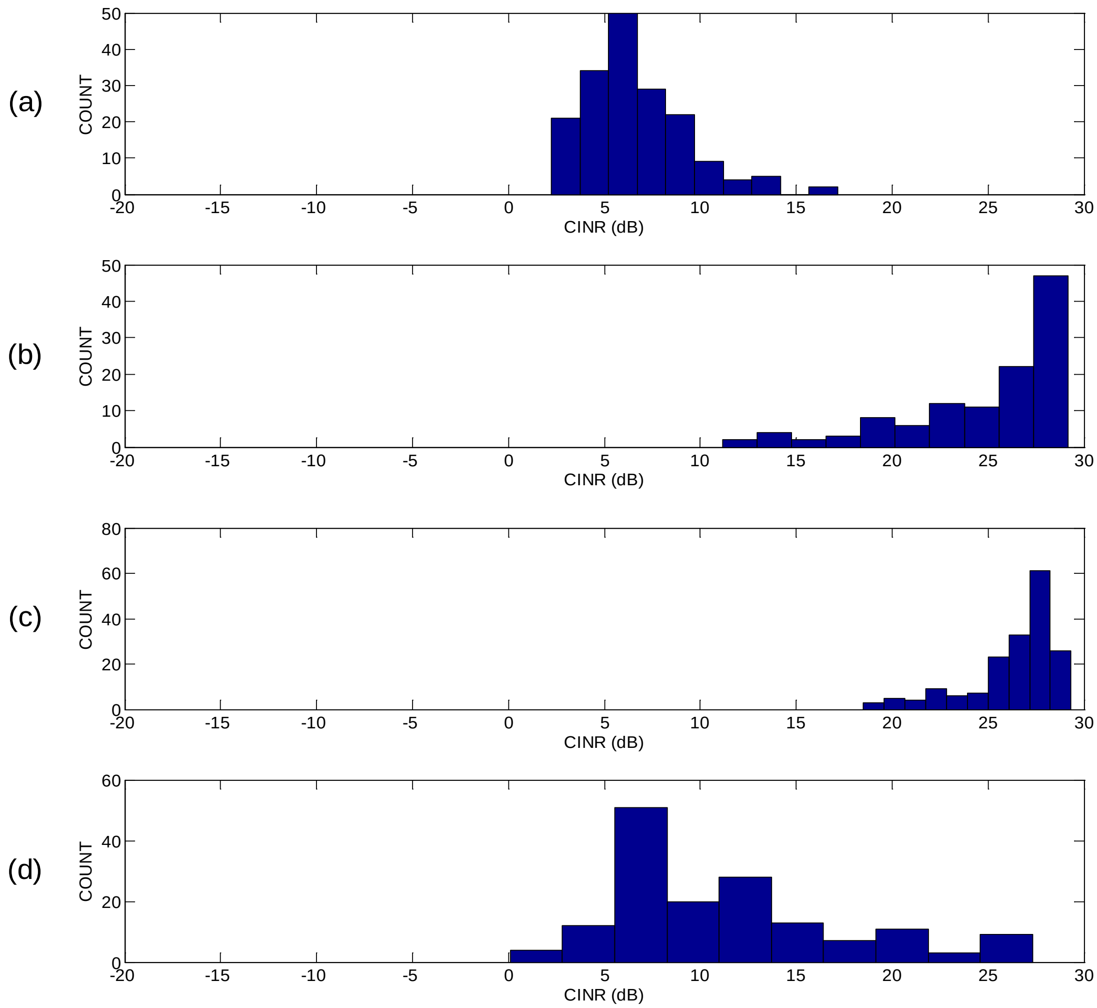

Figure 135. Outside ground level histograms of CINR for different coverage combinations with a UDP downlink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas and PSCR MN.

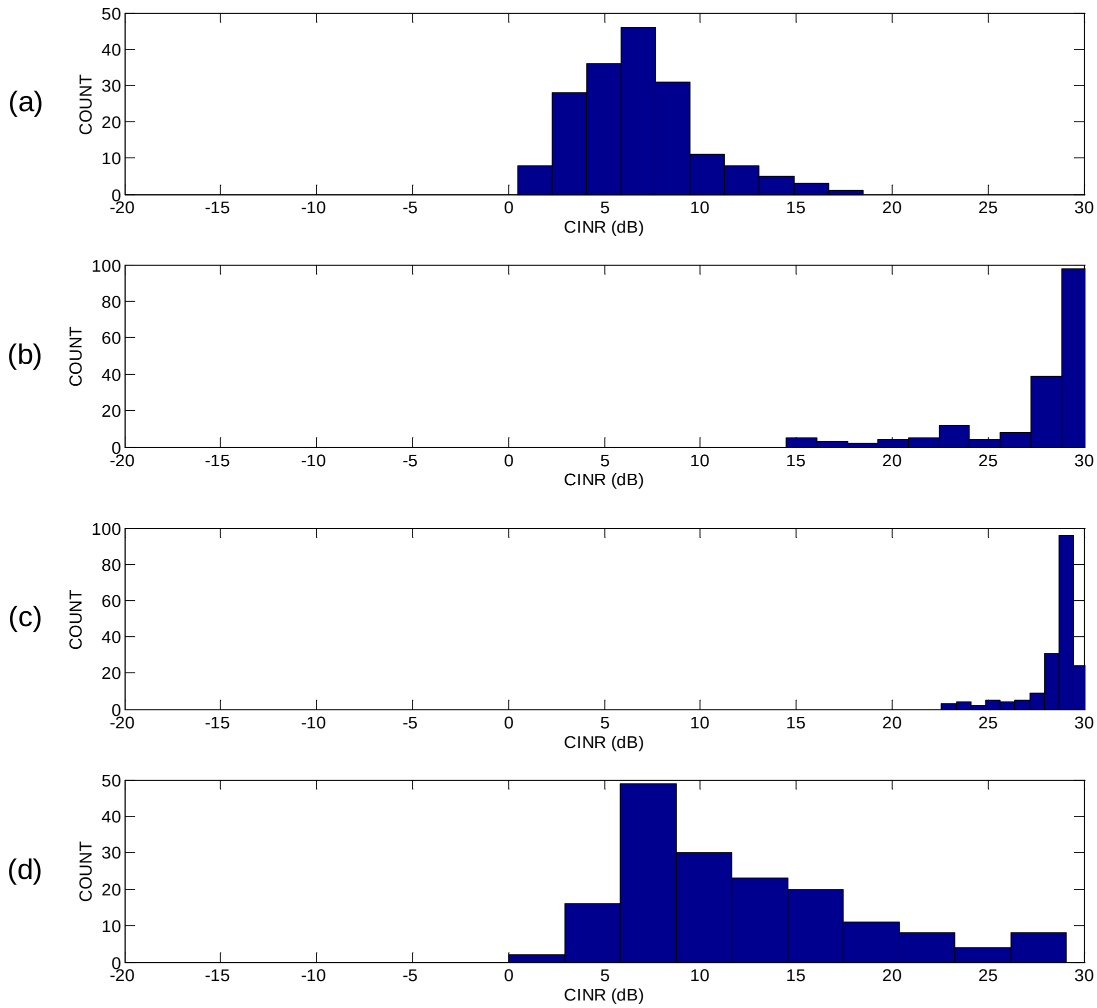

Figure 136. Outside ground level histograms of CINR for different coverage combinations with a UDP uplink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas and PSCR MN.

Table 71. Outside ground level CINR statistics for a UDP downlink data flow.

Coverage Combination	**Mean CINR (dB)**	**Median CINR (dB)**	**Standard Deviation (dB)**	**Min CINR (dB)**	**Max CINR (dB)**
PSCR MN	6.6	6.2	2.7	2.2	17.2
COW 8 W	24.9	26.8	4.4	11.2	29.2
COW 40 W	26.3	27.1	2.3	18.5	29.3
SCDA 5 W + PSCR MN	11.4	10.0	6.1	0.1	27.3

Table 72. Outside ground level CINR statistics for a UDP uplink data flow.

Coverage Combination	**Mean CINR (dB)**	**Median CINR (dB)**	**Standard Deviation (dB)**	**Min CINR (dB)**	**Max CINR (dB)**
PSCR MN	6.8	6.5	3.2	0.5	18.5
COW 8 W	27.3	28.9	3.6	14.5	30.4
COW 40 W	28.5	28.9	1.5	22.6	30.2
SCDA 5 W + PSCR MN	12.1	10.8	6.4	0.0	29.1

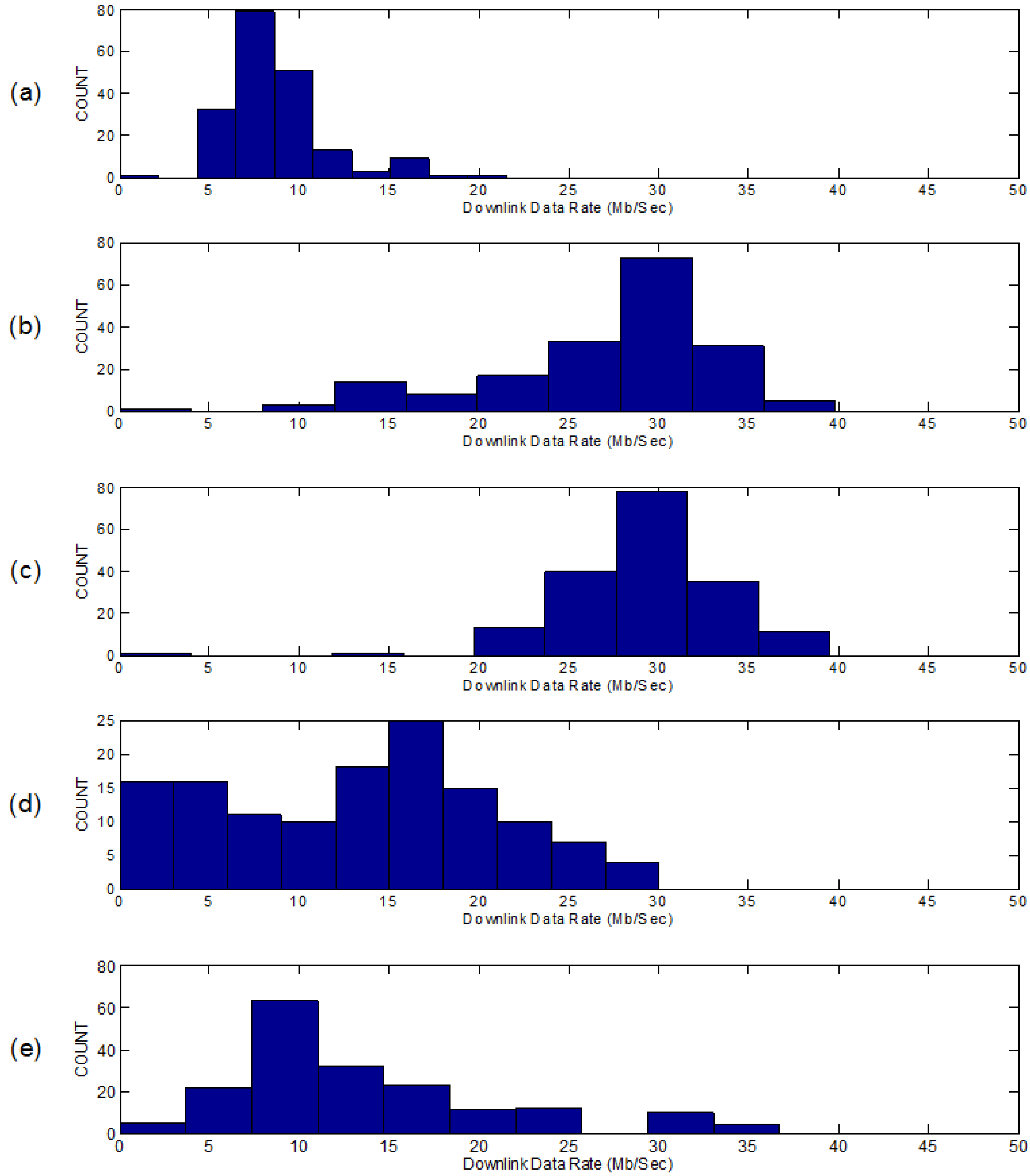

Figure 137. Outside ground level histograms of PDSCH for different coverage combinations with a TCP downlink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas, (e) small cell at 5 W with discrete antennas and PSCR MN.

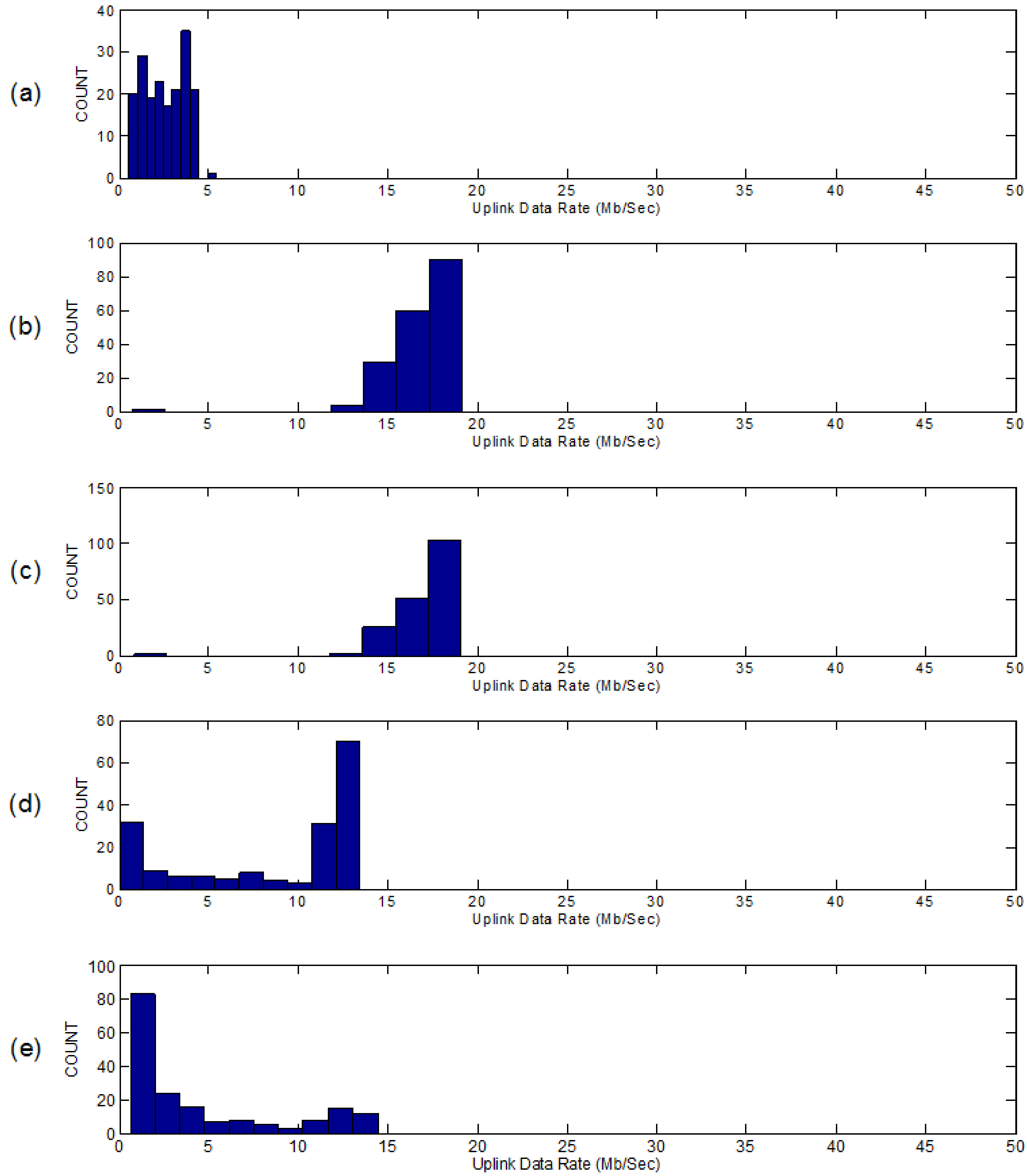

Figure 138. Outside ground level histograms of PUSCH for different coverage combinations with a TCP uplink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas, (e) small cell at 5 W with discrete antennas and PSCR MN.

Table 73. PDSCH downlink data rate statistics for a TCP downlink data flow.

Coverage Combination	**Mean PDSCH (Mb/s)**	**Median PDSCH (Mb/s)**	**Standard Deviation (Mb/s)**	**Min PDSCH (Mb/s)**	**Max PDSCH (Mb/s)**
PSCR MN	8.7	8.1	2.8	0.0	21.5
COW 8 W	27.2	28.8	3.4	0.0	39.8
COW 40 W	29.3	29.5	4.4	16.8	39.5
SCDA 5 W	13.2	14.0	7.7	0.0	30.1
SCDA 5 W + PSCR MN	13.7	11.2	7.4	0.0	36.7

Table 74. PUSCH uplink data rate statistics for a TCP uplink data flow.

Coverage Combination	**Mean PUSCH (Mb/s)**	**Median PUSCH (Mb/s)**	**Standard Deviation (Mb/s)**	**Min PUSCH (Mb/s)**	**Max PUSCH (Mb/s)**
PSCR MN	3.5	2.5	1.5	1.5	5.4
COW 8 W	16.9	17.3	1.8	0.7	19.1
COW 40 W	17.0	17.6	1.8	0.8	19.1
SCDA 5 W	8.5	12.0	4.9	0.0	13.5
SCDA 5 W + PSCR MN	4.6	2.3	4.4	0.6	14.4

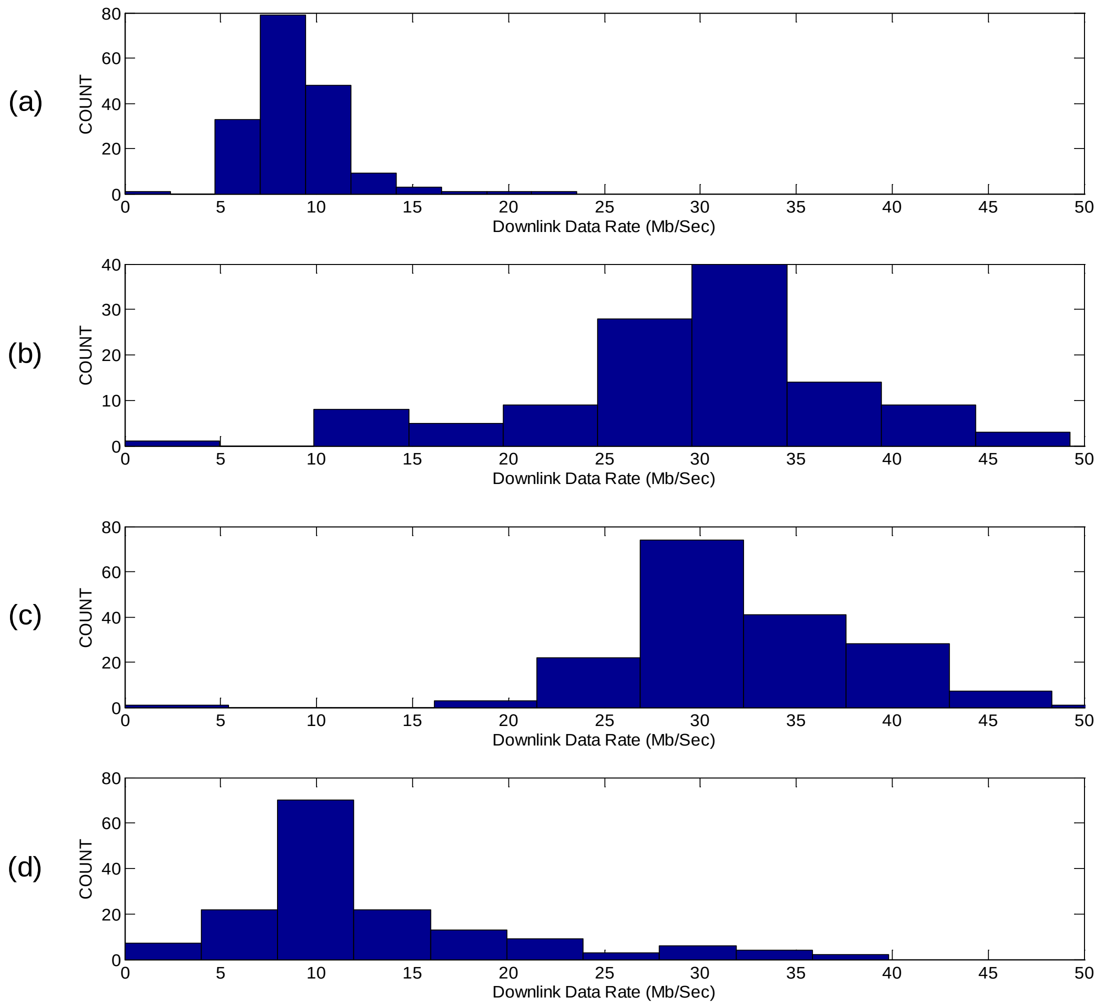

Figure 139. Outside ground level histograms of PDSCH for different coverage combinations with a UDP downlink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas and PSCR MN.

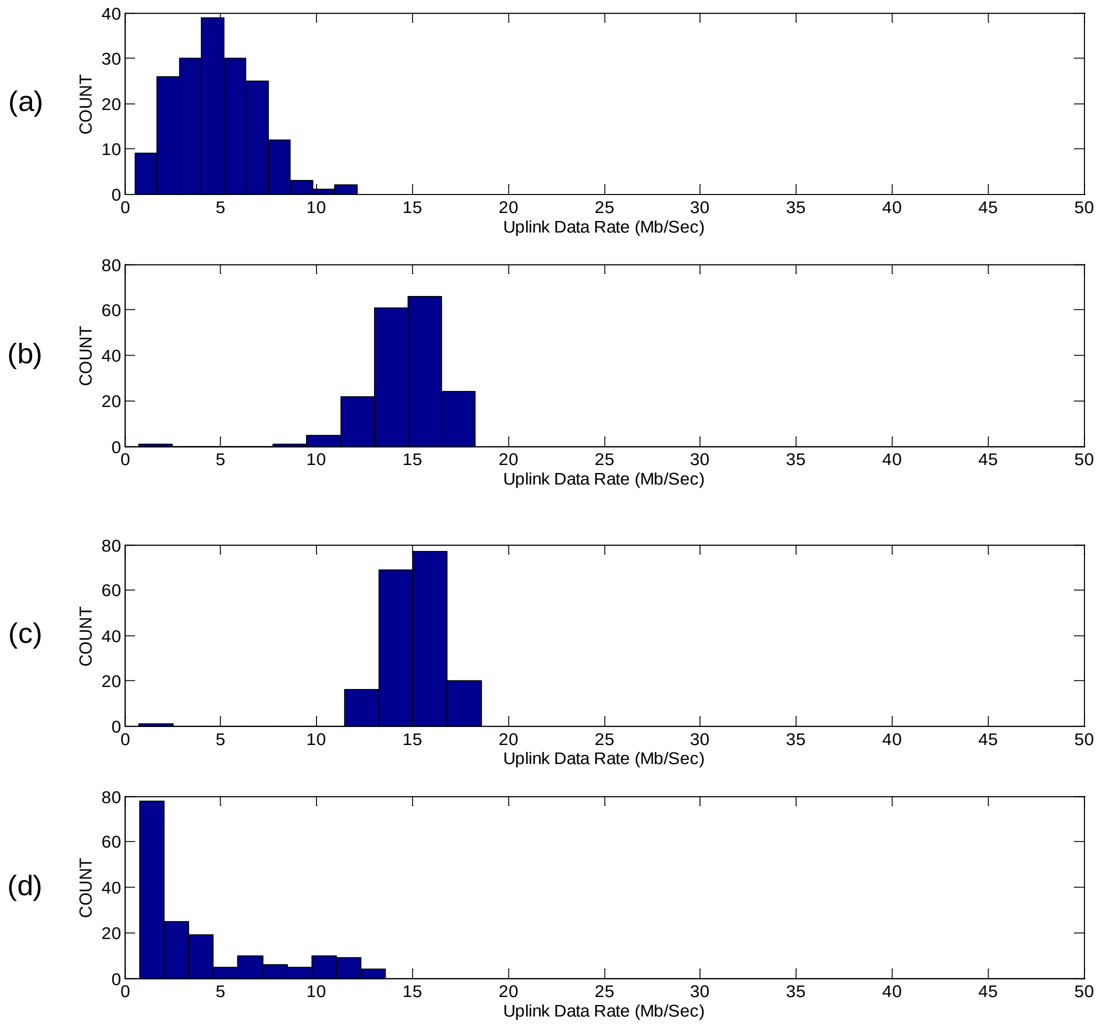

Figure 140. Outside ground level histograms of PDSCH for different coverage combinations with a UDP downlink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas and PSCR MN.

Table 75. PDSCH downlink data rate statistics for a UDP downlink data flow.

Coverage Combination	**Mean PDSCH (Mb/s)**	**Median PDSCH (Mb/s)**	**Standard Deviation (Mb/s)**	**Min PDSCH (Mb/s)**	**Max PDSCH (Mb/s)**
PSCR MN	9.0	8.7	2.6	0.0	23.6
COW 8 W	29.4	29.9	8.2	0.0	49.3
COW 40 W	32.1	30.9	6.5	0.0	53.7
SCDA 5 W + PSCR MN	12.8	10.1	7.6	0.0	39.8

Table 76. PUSCH downlink data rate statistics for a UDP uplink data flow.

Coverage Combination	Mean PUSCH (Mb/s)	Median PUSCH (Mb/s)	Standard Deviation (Mb/s)	Min PUSCH (Mb/s)	Max PUSCH (Mb/s)
PSCR MN	4.7	4.5	2.1	0.5	12.1
COW 8 W	14.7	14.8	2.0	0.7	18.3
COW 40 W	15.0	15.1	1.8	0.7	18.6
SCDA 5 W + PSCR MN	4.0	2.3	3.6	0.8	13.6

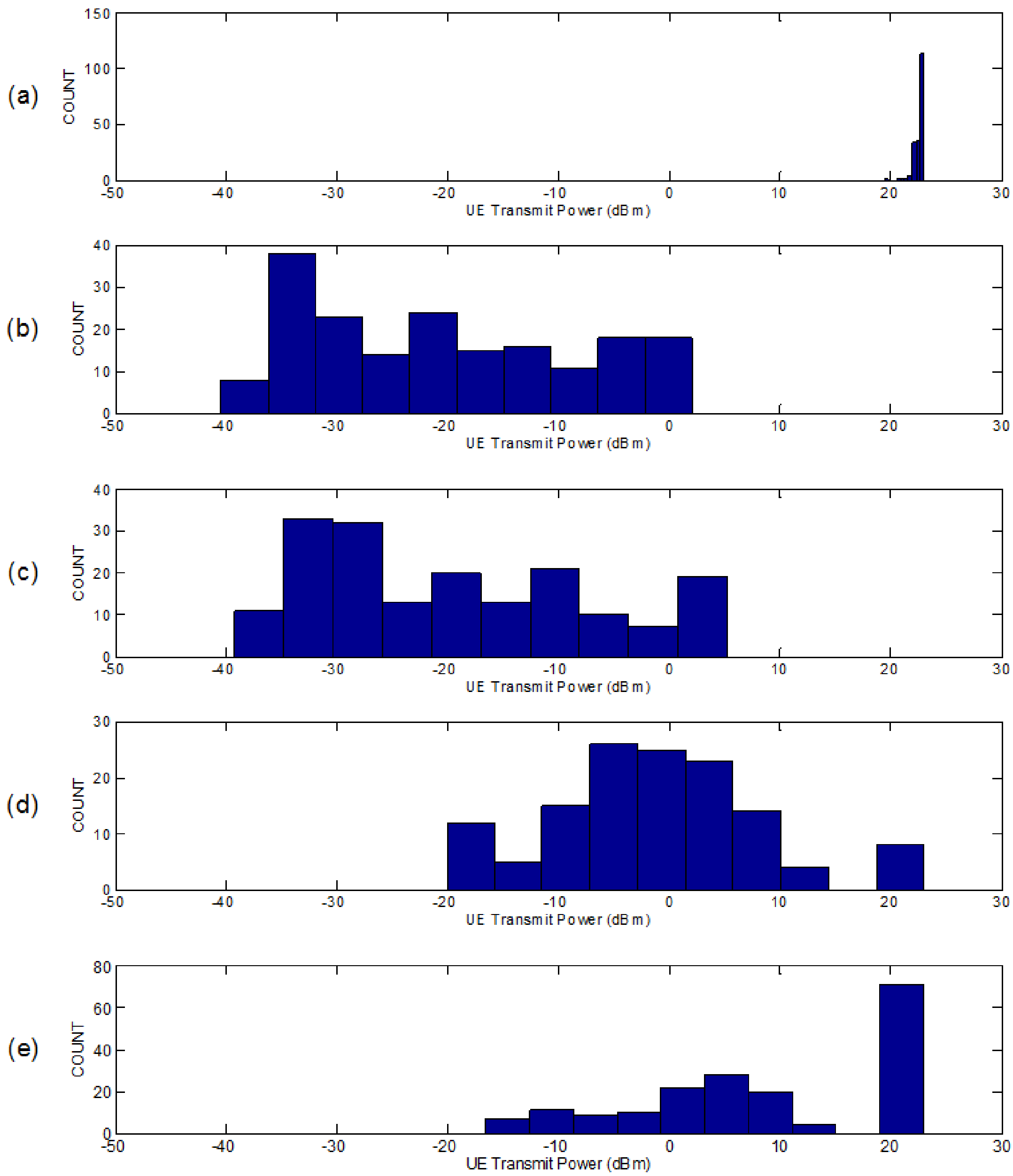

Figure 141. Outside ground level histograms of UE transmit power for different coverage combinations with a TCP downlink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas, (e) small cell at 5 W with discrete antennas and PSCR MN.

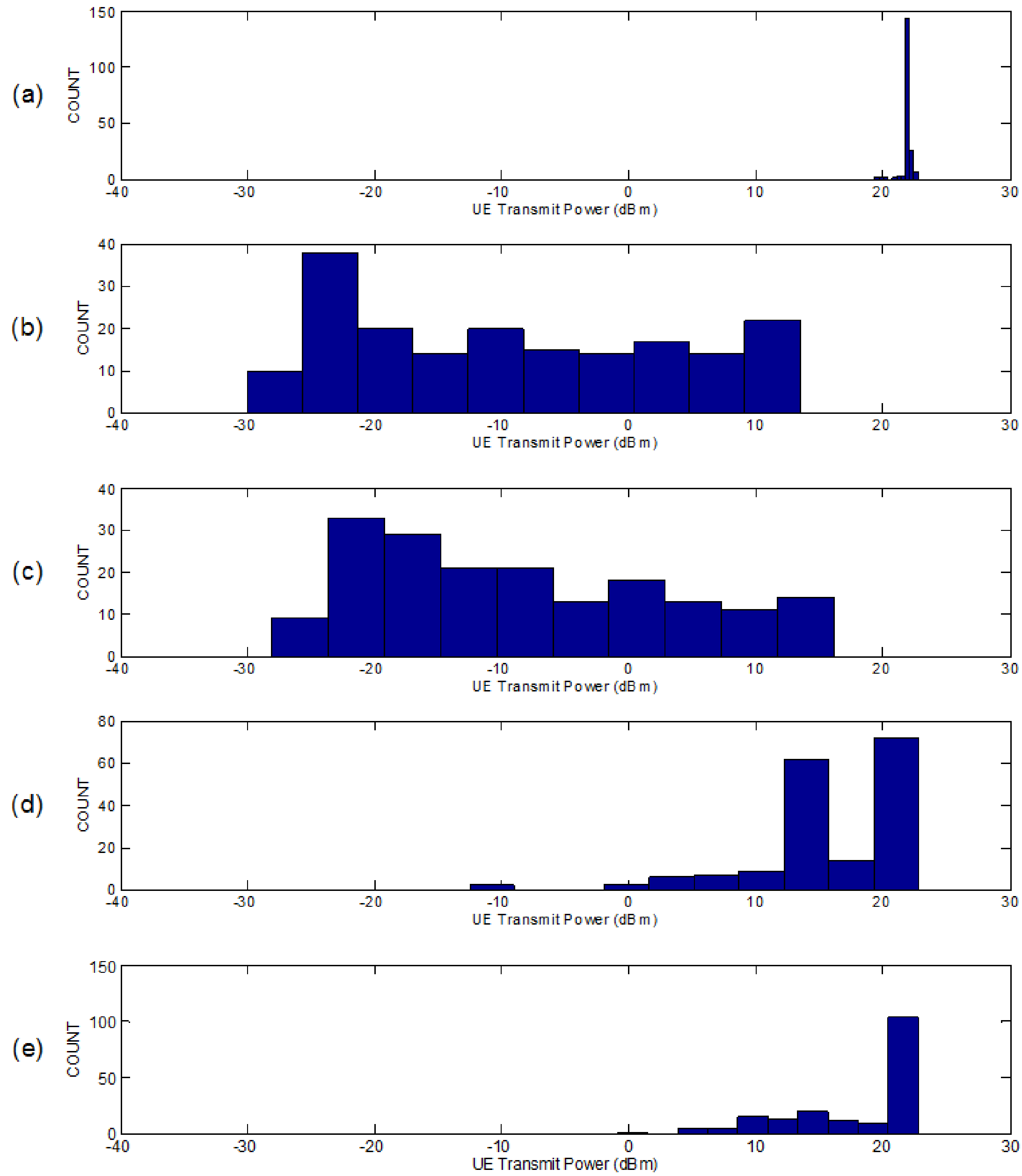

Figure 142. Outside ground level histograms of UE transmit power for different coverage combinations with a TCP uplink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas, (e) small cell at 5 W with discrete antennas and PSCR MN.

Table 77. Outside ground level UE transmit power characteristics for a TCP downlink data flow.

Coverage Combination	Mean UEpwr (dBm)	Median UEpwr (dBm)	Standard Deviation (dBm)	Min UEpwr (dBm)	Max UEpwr (dBm)
PSCR MN	22.6	22.7	0.5	19.5	23.0
COW 8 W	-20.4	-22.4	12.2	-40.5	2.0
COW 40 W	-19.4	-20.4	12.5	-39.2	5.2
SCDA 5 W	-1.3	-1.8	9.6	-20.1	23.0
SCDA 5 W + PSCR MN	9.4	7.7	12.2	-16.5	23.0

Table 78. Outside ground level UE transmit power characteristics for a TCP uplink data flow.

Coverage Combination	Mean UEpwr (dBm)	Median UEpwr (dBm)	Standard Deviation (dBm)	Min UEpwr (dBm)	Max UEpwr (dBm)
PSCR MN	22.0	22.0	0.4	19.3	22.8
COW 8 W	-9.1	-10.4	12.9	-30.0	13.5
COW 40 W	-8.7	-10.8	11.9	-28.1	16.1
SCDA 5 W	16.2	15.7	6.1	-12.5	22.9
SCDA 5 W + PSCR MN	18.1	21.4	5.2	-0.8	22.8

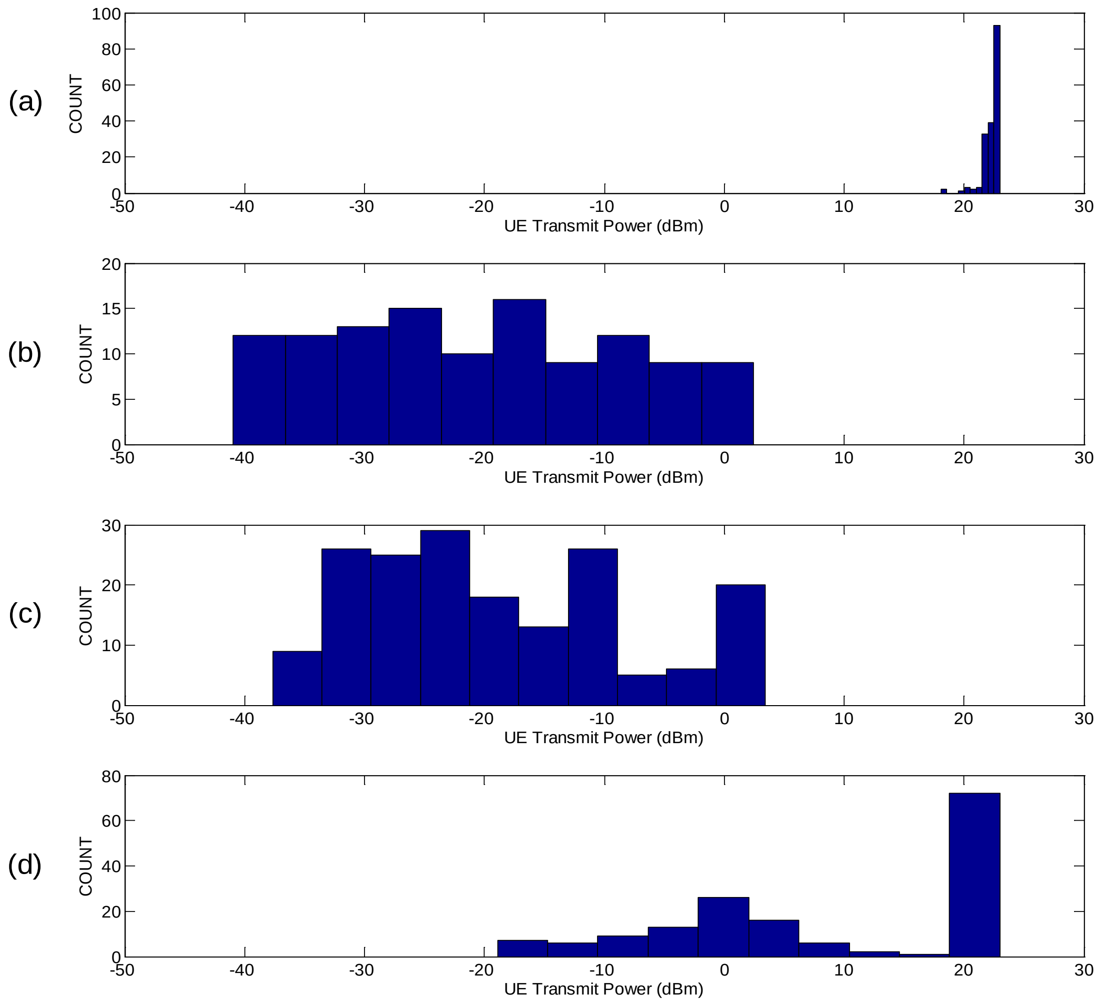

Figure 143. Outside ground level histograms of UE transmit power for different coverage combinations with a UDP downlink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas and PSCR MN.

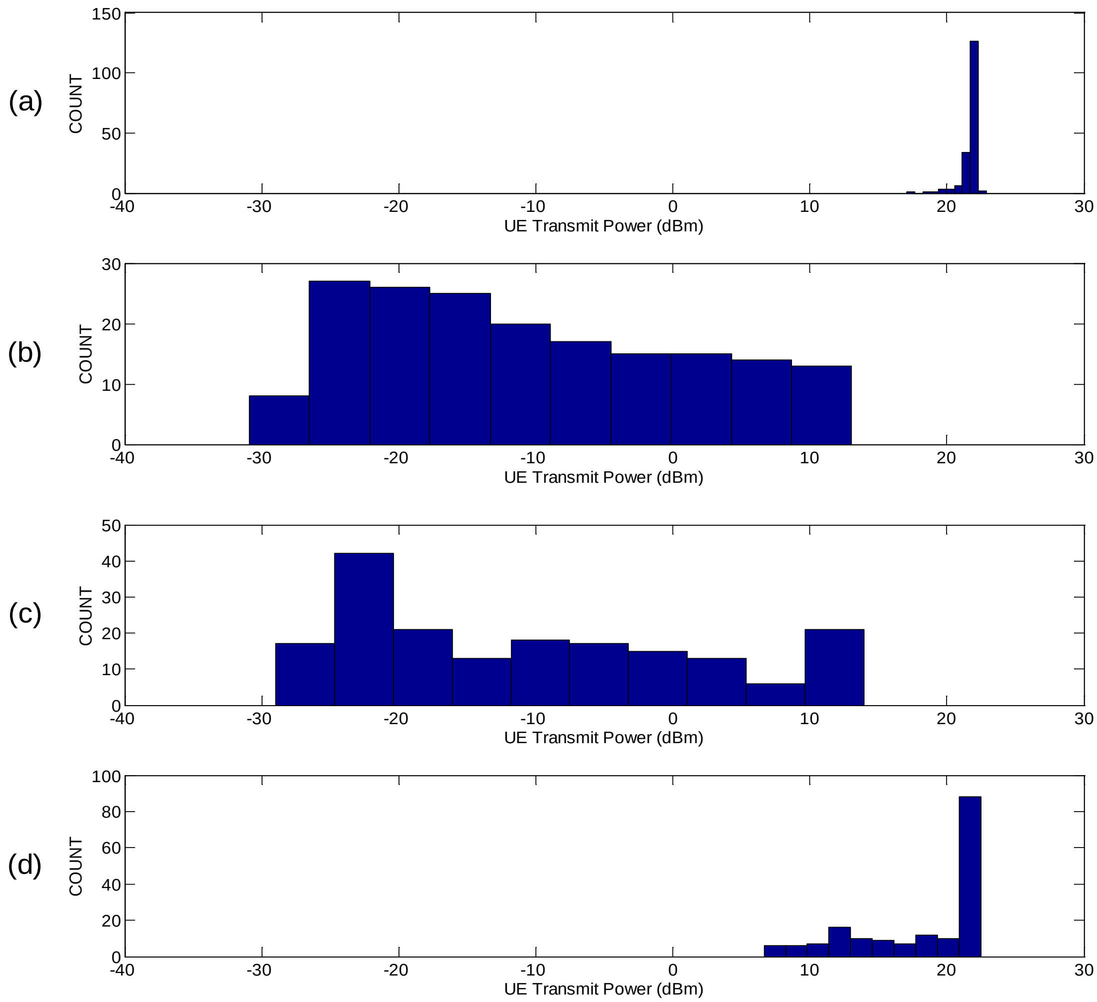

Figure 144. Outside ground level histograms of UE transmit power for different coverage combinations with a UDP uplink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W, (d) small cell at 5 W with discrete antennas and PSCR MN.

Table 79. Outside ground level UE transmit statistics for a UDP downlink data flow.

Coverage Combination	**Mean UEpwr (dBm)**	**Median UEpwr (dBm)**	**Standard Deviation (dBm)**	**Min UEpwr (dBm)**	**Max UEpwr (dBm)**
PSCR MN	22.4	22.5	0.7	18.1	23.0
COW 8 W	-20.5	-21.6	11.9	-41.0	2.4
COW 40 W	-19.0	-21.4	11.1	-37.7	3.4
SCDA 5 W + PSCR MN	9.0	7.2	13.7	-19.0	23.0

Table 80. Outside ground level UE transmit statistics for a UDP uplink data flow.

Coverage Combination	Mean UEpwr (dBm)	Median UEpwr (dBm)	Standard Deviation (dBm)	Min UEpwr (dBm)	Max UEpwr (dBm)
PSCR MN	21.7	22.0	0.6	17.1	22.9
COW 8 W	-10.6	-12.5	11.8	-31.0	13.0
COW 40 W	-10.4	-12.0	12.5	-29.0	14.0
SCDA 5 W + PSCR MN	18.2	4.7	6.7	6.7	22.5

3.6 DLC Royal Terrace Measured Results

The Royal Terrace walk test path is short, simple, and located outdoors. The walk path, described in Section 2.1, is a closed rectangular contour that follows the outer perimeter of the Royal Terrace. The Royal Terrace is accessed through two different doors located on level 2, on the east side of the DLC. The Royal Terrace is situated two floors above the street level, and portions of the walk path experience line-of-sight conditions to the Green Mountain eNB. The fewest data points were obtained here due to the relatively short length of the walk path.

Results were obtained on the Royal Terrace for the three coverage combinations:

- PSCR MN only
- COW only at 8 W
- COW only at 40 W

Figures 145–147 depict the RSRP levels for a TCP downlink data flow for the three macro network and COW coverage combinations. Histograms of RSRP are given in Figures 148–151 for both a downlink and an uplink data flow, using TCP and UDP transfer protocols. The associated summary statistics are given in Tables 81–84. The PSCR MN provides the best coverage on the east side of the walk path, since line-of-sight conditions occur there. Reduced signal levels are seen on the remainder of the walk path due to blockage effects of the DLC building itself. The COW dramatically improves the signal levels, as the histograms indicate. Typical improvements of 25–30 dB in signal levels are noted. This is attributed to an unobstructed path to the COW and a greatly reduced eNB to UE separation.

Figures 152–155 depict the CINR results for the four data flow combinations. The summary statistics are provided in Tables 85–88. The CINR values vary from 5 to 22 dB with the PSCR MN. The results improve significantly with the COW at transmit power levels of either 8 W or 40 W. The CINR values are tightly clustered in the range of 26 to 30 dB.

The PDSCH downlink data rate histograms are presented in Figures 156 and 158 for TCP and UDP respectively. Statistical summaries are provided in Tables 89 and 91. The PSCR MN produces data rates in the range of 6–35 Mb/s. This wide variation of data rates is due to the combination of line-of-sight and non-line-of-sight conditions that occur over the walk path. The situation is ameliorated when the COW is active and much higher downlink data rates occur. We see data rates in excess of 35 Mb/s for TCP and data rates exceeding 45 Mb/s are seen with UDP.

The PUSCH uplink data rates, which are shown in Figures 157 and 159, exhibit similar trends as a function of coverage. Summary statistics are given in Tables 90 and 92. For TCP, a wide spread of data rates occurs with a range of 2.4–12 Mb/s encountered over the walk path when the PSCR MN provides coverage. The corresponding uplink data rate range for UDP is 1–10 Mb/s. When the COW provides coverage at either 8 W or 40 W, the resulting TCP data rates are tightly clustered in the range of 15–19 Mb/s—a major improvement. Similar improvements are observed with UDP.

The UE transmit power histograms are presented in Figures 160–163. The associated statistics are provided in Tables 93–96. High counts of power levels in excess of +20 dBm are seen when the PSCR MN provides coverage, which is due to high path losses between the UE and the Green Mountain eNB. The required UE transmit power levels are greatly reduced when the COW is providing coverage.

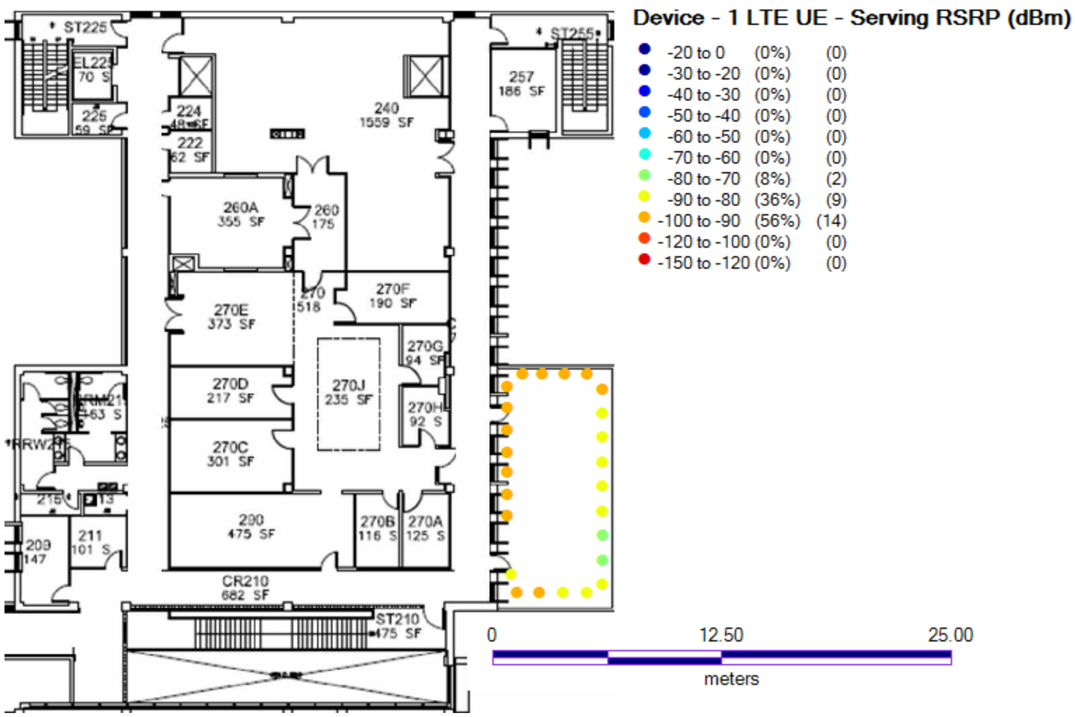

Figure 145. Royal Terrace reference signal received power (RSRP) for a TCP downlink data flow with the PSCR MN. North is at the top of the figure.

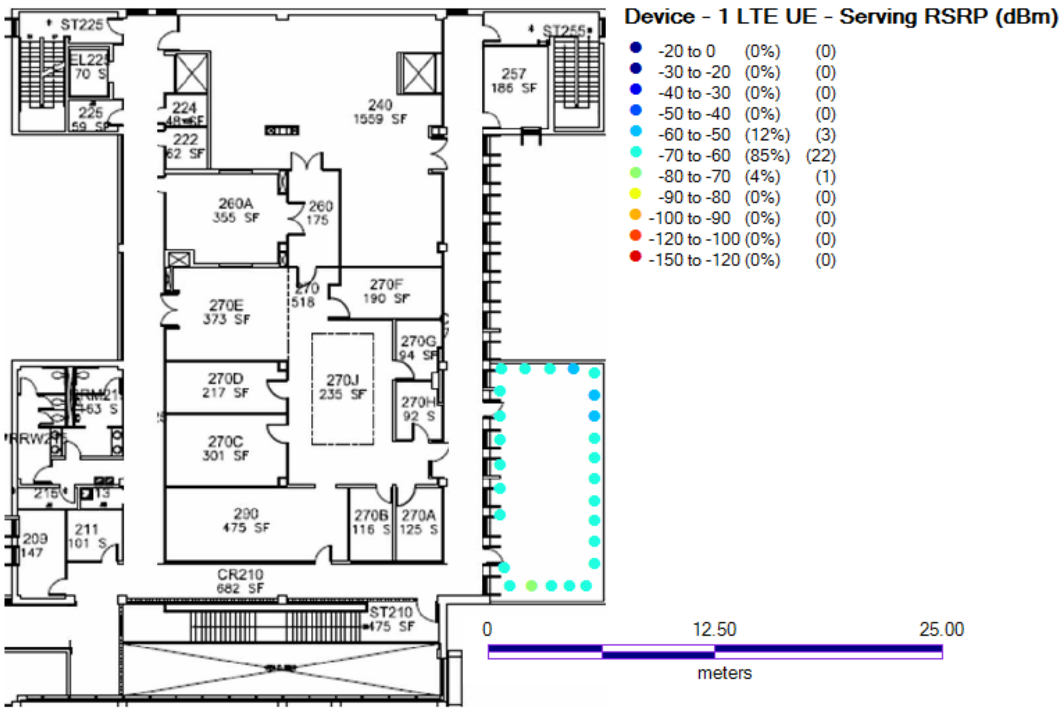

Figure 146. Royal Terrace reference signal received power (RSRP) for a TCP downlink data flow with the PSCR MN and a COW at 8 W. North is at the top of the figure.

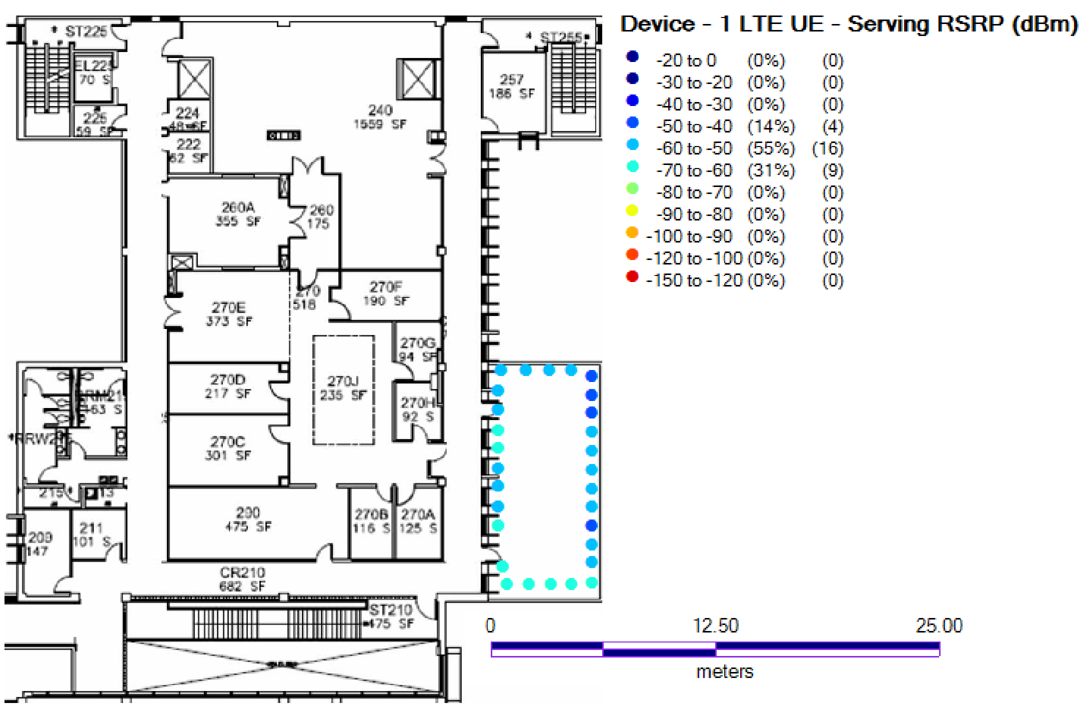

Figure 147. Royal Terrace reference signal received power (RSRP) for a TCP downlink data flow with the PSCR MN and a COW at 40 W. North is at the top of the figure.

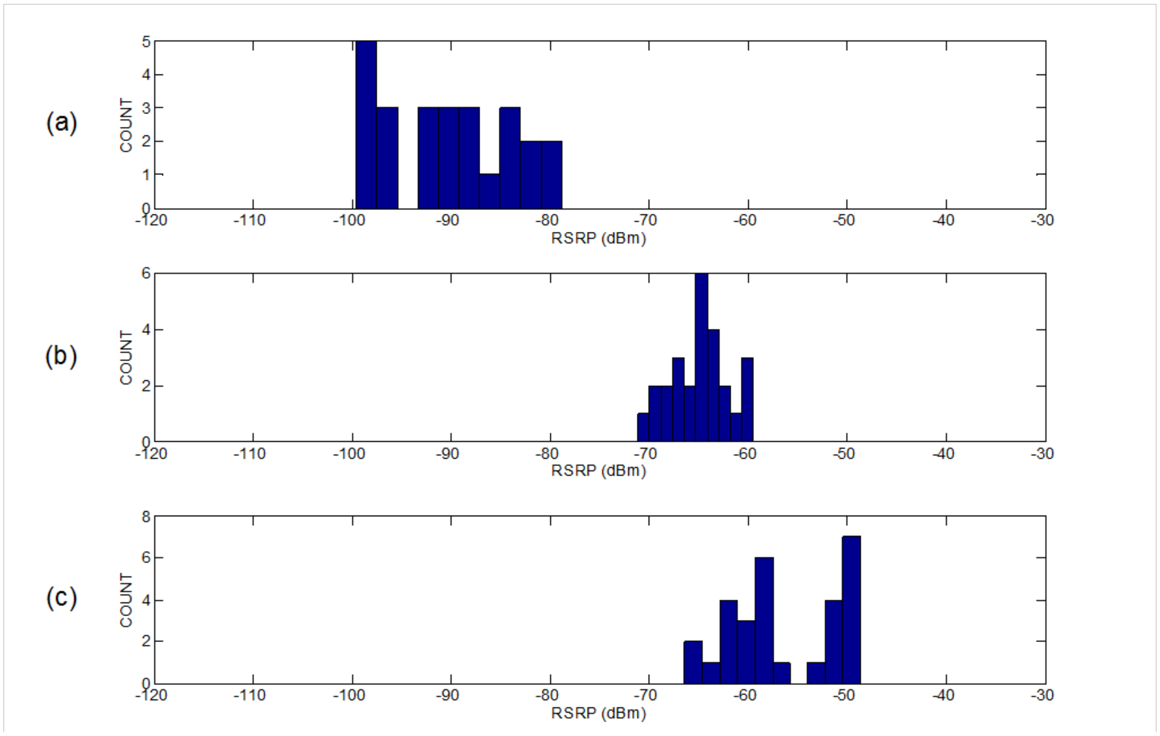

Figure 148. Royal Terrace histograms serving cell RSRP for different coverage combinations with a TCP downlink data flow. (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W.

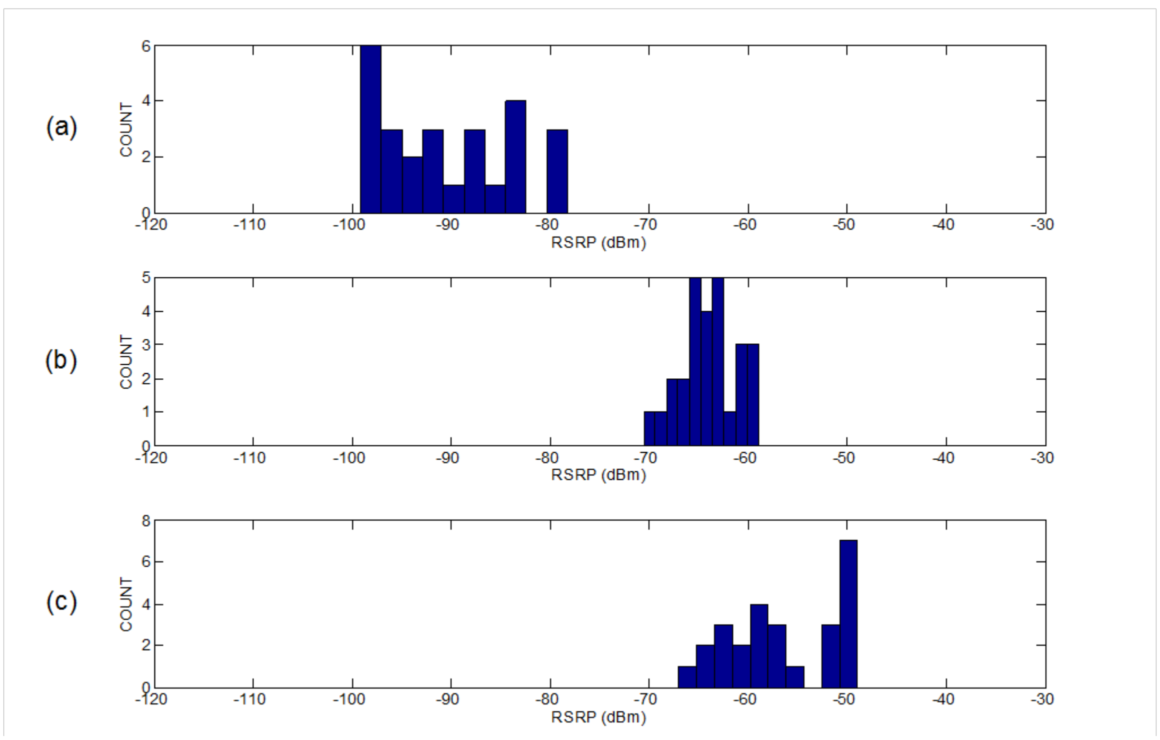

Figure 149. Royal Terrace histograms of serving cell RSRP for different coverage combinations with a TCP uplink data flow, (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W.

Table 81. Royal Terrace RSRP statistics for a TCP downlink data flow.

Coverage Combination	Mean RSRP (dBm)	Median RSRP (dBm)	Standard Deviation (dBm)	Min RSRP (dBm)	Max RSRP (dBm)
PSCR MN	-90.3	-90.8	6.4	-99.5	-78.9
COW 8 W	-64.9	-65.0	3.1	-71.2	-59.5
COW 40 W	-56.4	-57.9	5.7	-66.5	-48.7

Table 82. Royal Terrace RSRP statistics for a TCP uplink data flow.

Coverage Combination	Mean RSRP (dBm)	Median RSRP (dBm)	Standard Deviation (dBm)	Min RSRP (dBm)	Max RSRP (dBm)
PSCR MN	-90.6	-91.6	6.8	-99.1	-78.2
COW 8 W	-64.0	-64.0	3.0	-70.6	-59.0
COW 40 W	-56.4	-57.2	5.7	-37.0	-49.0

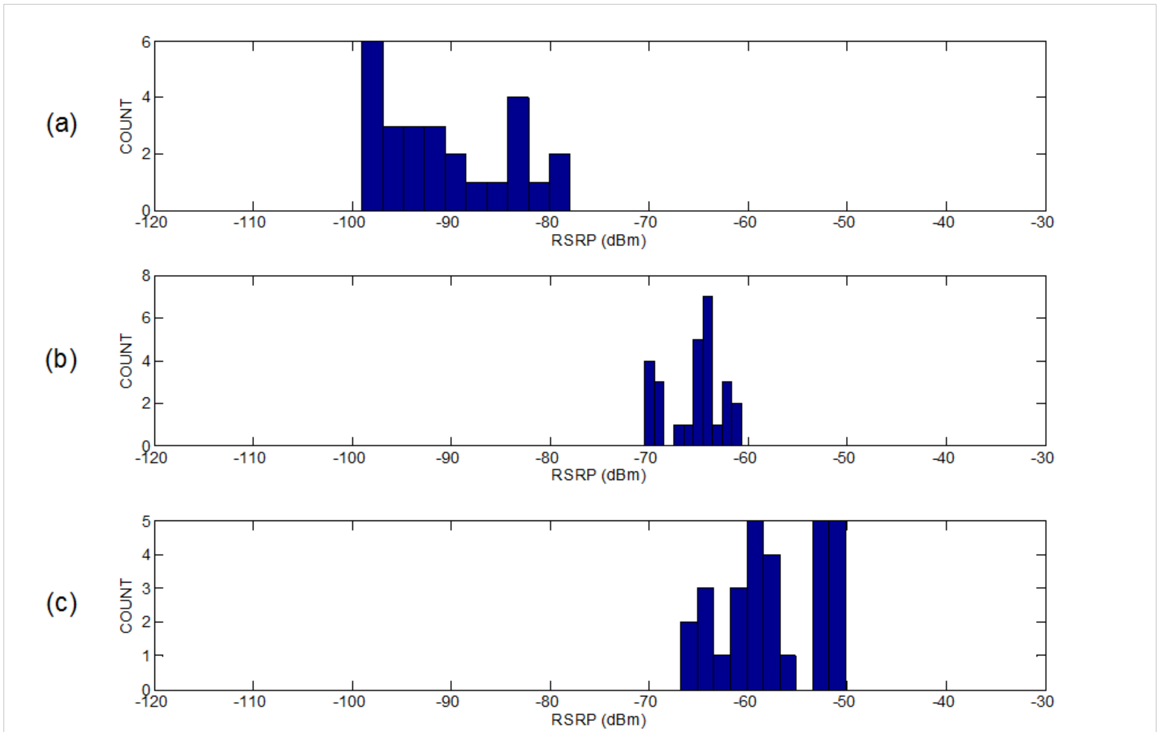

Figure 150. Royal Terrace histograms of serving cell RSRP for different coverage combinations with a UDP downlink data flow, (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W.

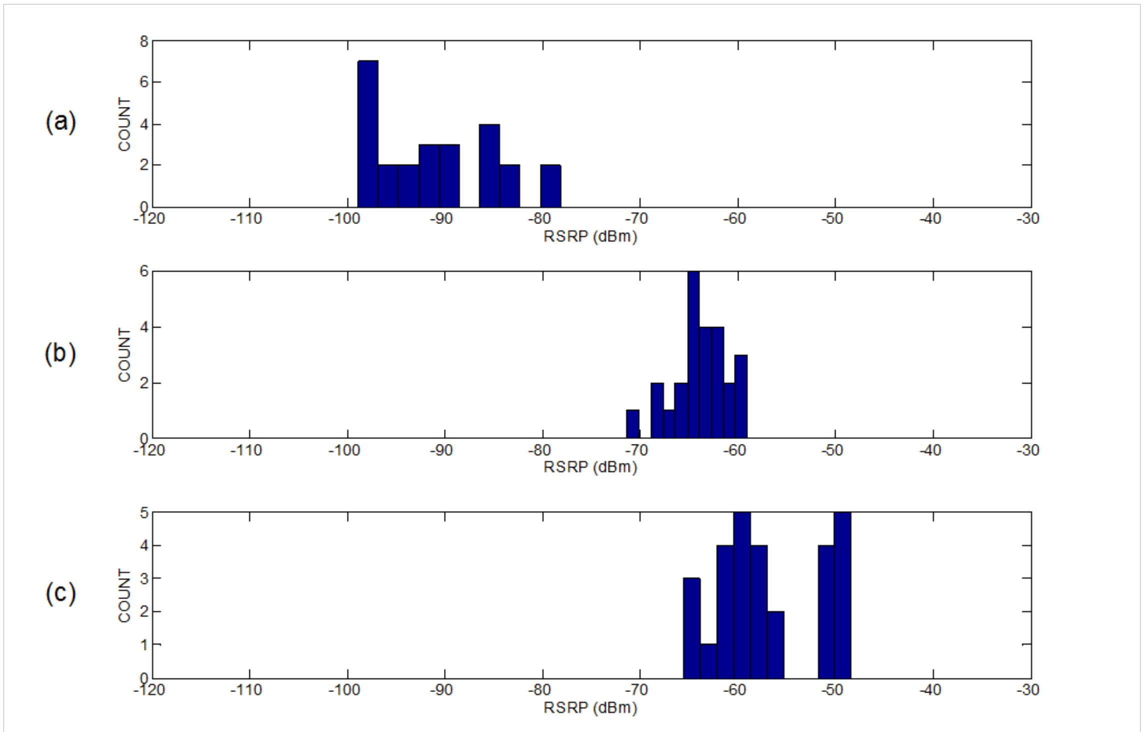

Figure 151. Royal Terrace histograms of serving cell RSRP for different coverage combinations with a UDP uplink data flow, (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W.

Table 83. Royal Terrace RSRP statistics for a UDP downlink data flow.

Coverage Combination	**Mean RSRP (dBm)**	**Median RSRP (dBm)**	**Standard Deviation (dBm)**	**Min RSRP (dBm)**	**Max RSRP (dBm)**
PSCR MN	-90.7	-92.1	6.7	-99.0	-78.0
COW 8 W	-65.4	-65.0	2.9	-70.4	-60.7
COW 40 W	-57.6	-58.5	5.1	-66.8	-50.2

Table 84. Royal Terrace RSRP statistics for a UDP uplink data flow.

Coverage Combination	**Mean RSRP (dBm)**	**Median RSRP (dBm)**	**Standard Deviation (dBm)**	**Min RSRP (dBm)**	**Max RSRP (dBm)**
PSCR MN	-91.1	-92.2	6.5	-98.9	-78.2
COW 8 W	-63.9	-63.5	3.0	-71.3	--59.1
COW 40 W	-57.0	-58.3	5.5	-65.6	-48.4

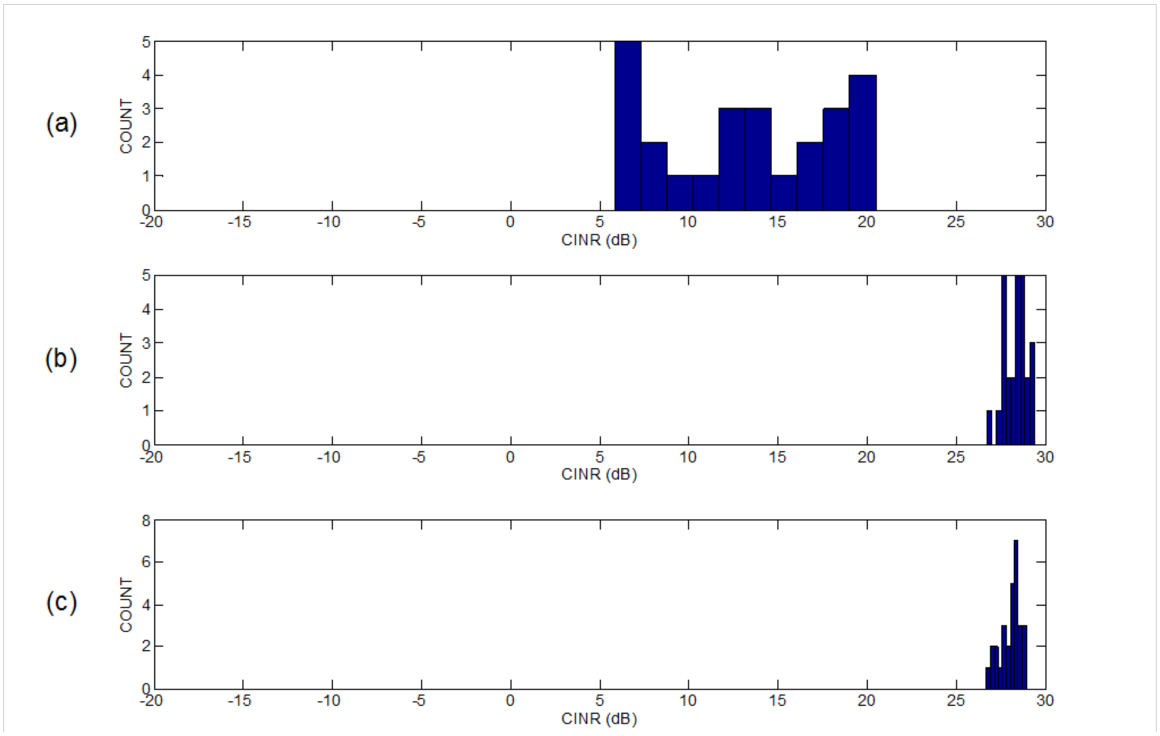

Figure 152. Royal Terrace histograms of serving cell CINR for different coverage combinations with a TCP downlink data flow, (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W.

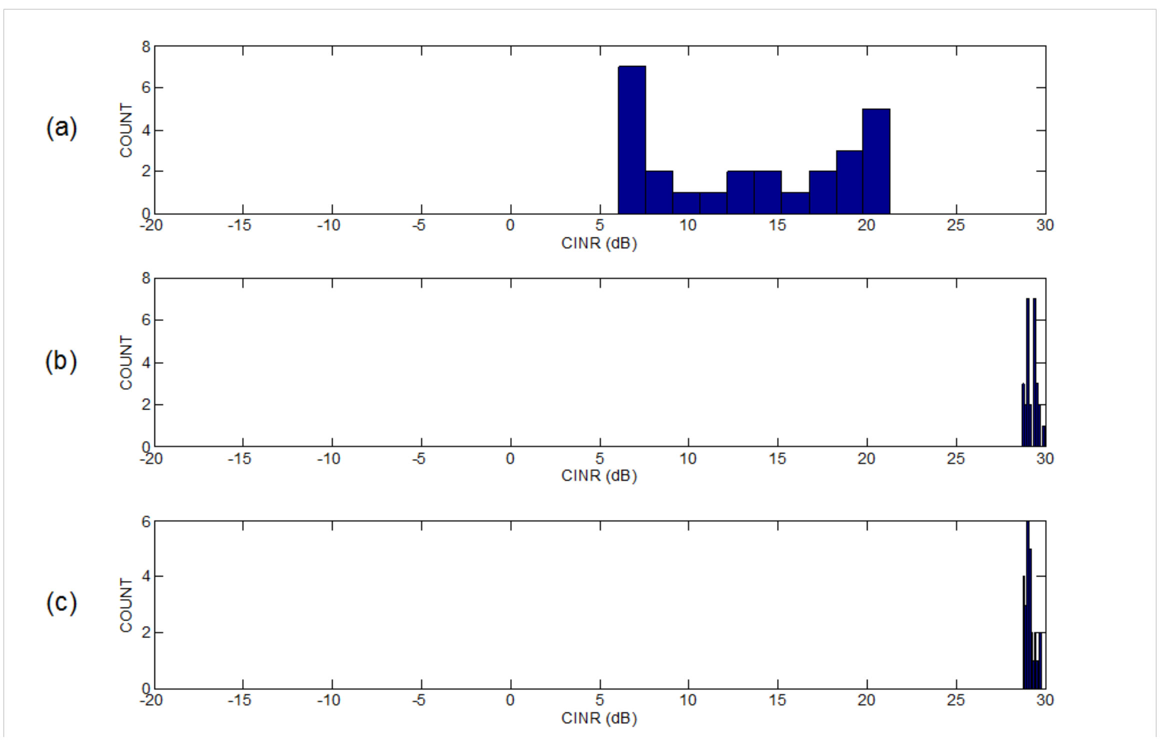

Figure 153 Royal Terrace histograms of serving cell CINR for different coverage combinations with a TCP uplink data flow, (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W.

Table 85. Royal Terrace CINR statistics for a TCP downlink data flow.

Coverage Combination	Mean CINR (dB)	Median CINR (dB)	Standard Deviation (dB)	Min CINR (dB)	Max CINR (dB)
PSCR MN	13.1	13.3	13.3	5.8	20.5
COW 8 W	28.3	28.4	28.4	26.7	29.4
COW 40 W	28.0	28.2	28.2	26.7	28.9

Table 86. Royal Terrace CINR statistics for a TCP uplink data flow.

Coverage Combination	Mean CINR (dB)	Median CINR (dB)	Standard Deviation (dB)	Min CINR (dB)	Max CINR (dB)
PSCR MN	13.5	13.8	5.7	6.0	21.3
COW 8 W	29.2	29.2	0.3	28.7	30.0
COW 40 W	12.1	29.1	0.3	28.8	29.8

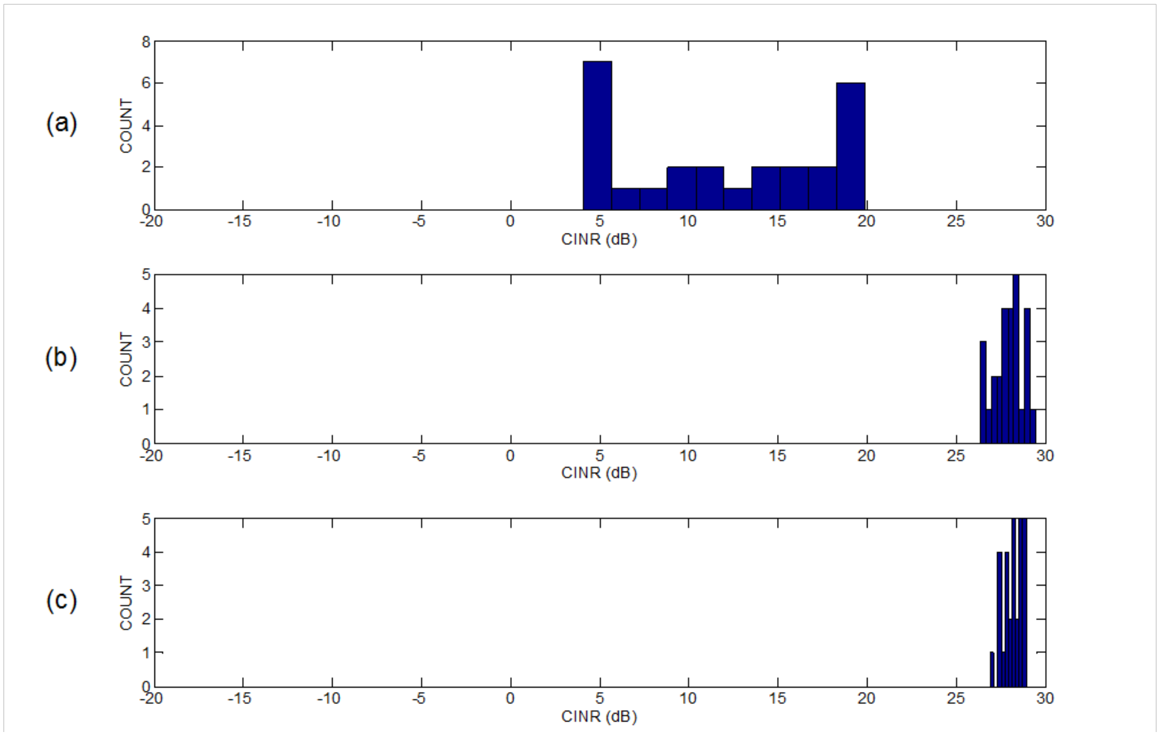

Figure 154 Royal Terrace histograms of serving cell CINR for different coverage combinations with a UDP downlink data flow, (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W.

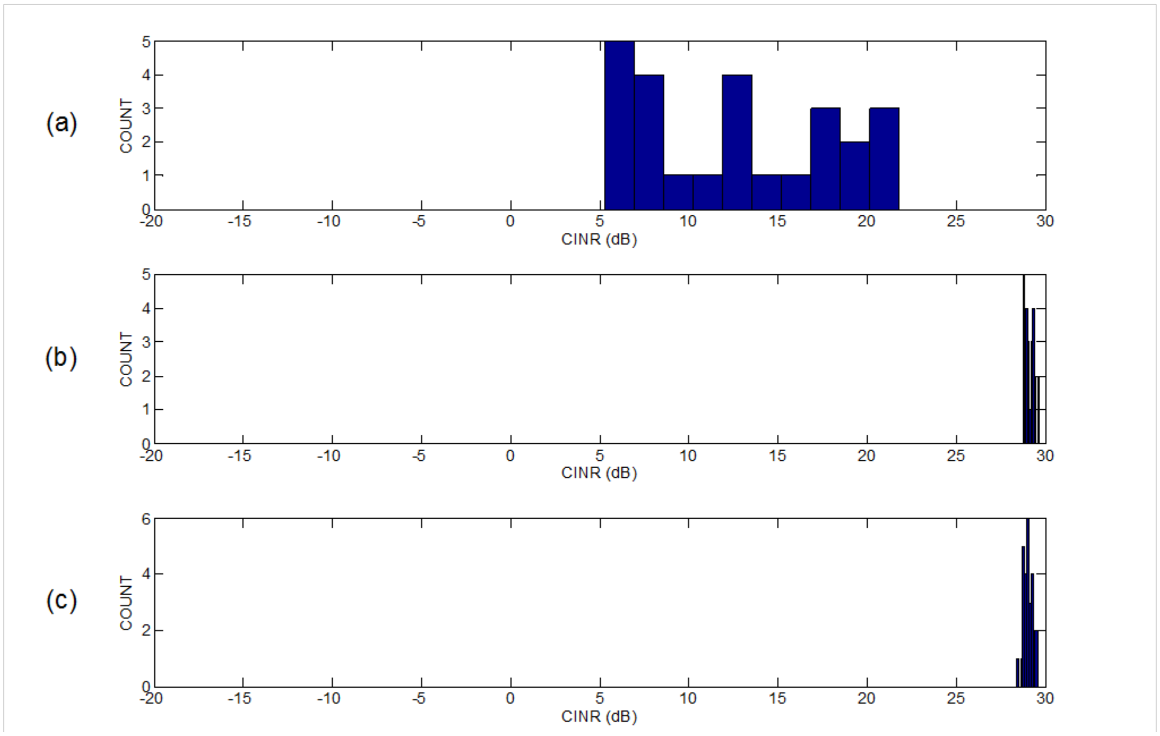

Figure 155. Royal Terrace histograms of serving cell CINR for different coverage combinations with a UDP uplink data flow, (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W.

Table 87. Royal Terrace CINR statistics for a UDP downlink data flow.

Coverage Combination	Mean CINR (dB)	Median CINR (dB)	Standard Deviation (dB)	Min CINR (dB)	Max CINR (dB)
PSCR MN	11.9	12.6	5.8	4.1	19.9
COW 8 W	27.9	28.0	0.9	26.3	29.4
COW 40 W	28.2	28.2	0.5	26.9	28.9

Table 88. Royal Terrace CINR statistics for a UDP uplink data flow.

Coverage Combination	Mean CINR (dB)	Median CINR (dB)	Standard Deviation (dB)	Min CINR (dB)	Max CINR (dB)
PSCR MN	12.8	12.8	5.6	5.3	21.8
COW 8 W	29.1	29.1	0.3	28.7	29.6
COW 40 W	29.0	29.0	0.3	28.4	29.6

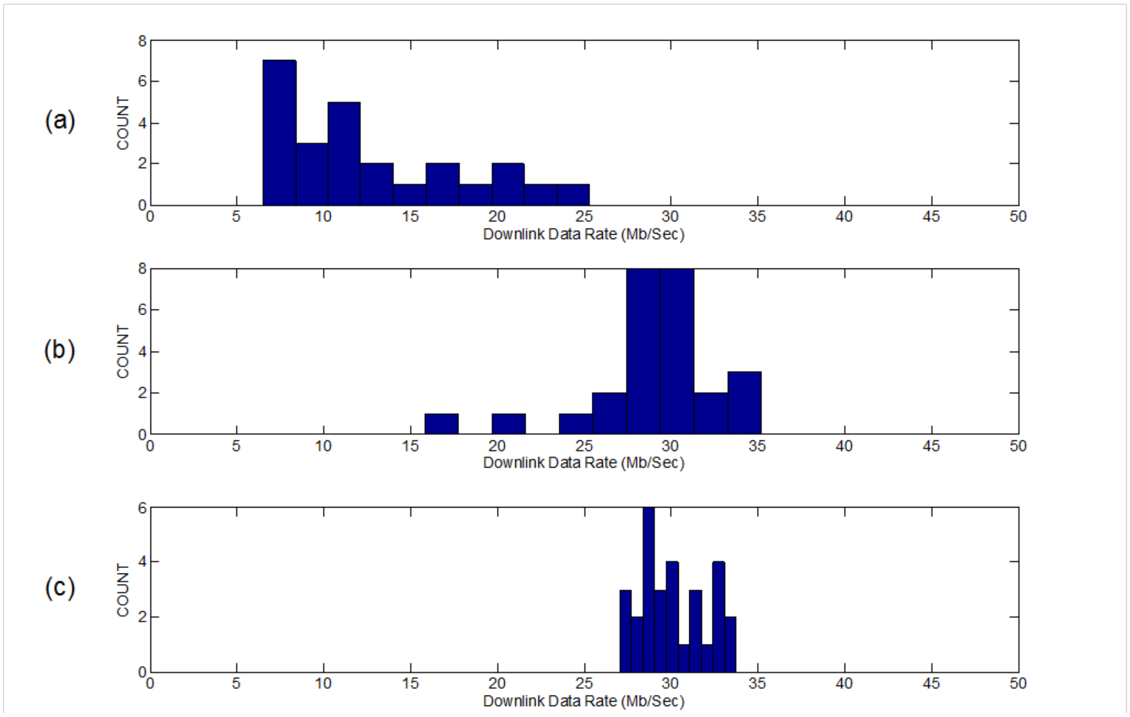

Figure 156. Royal Terrace histograms of serving cell PDSCH for different coverage combinations with a TCP downlink data flow, (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W.

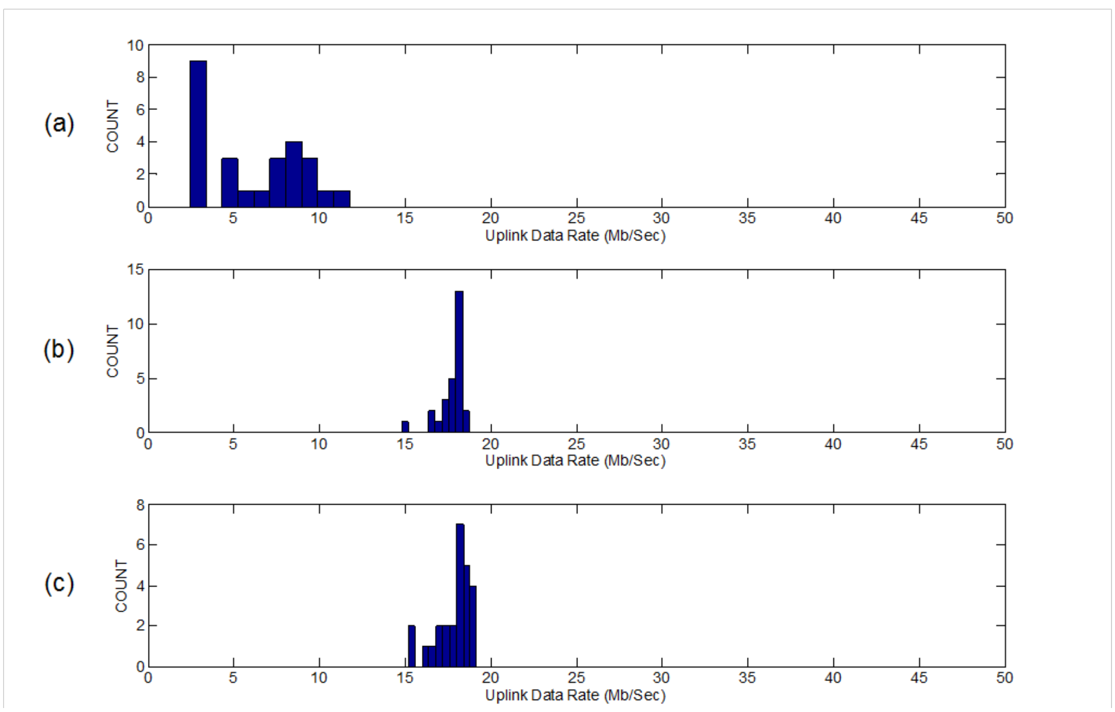

Figure 157. Royal Terrace histograms of serving cell PUSCH for different coverage combinations with a TCP uplink data flow, (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W.

Table 89. Royal terrace PDSCH statistics for a TCP downlink data flow.

Coverage Combination	Mean PDSCH (Mb/s)	Median PDSCH (Mb/s)	Standard Deviation (Mb/s)	Min PDSCH (Mb/s)	Max PDSCH (Mb/s)
PSCR MN	12.8	11.6	5.4	6.5	25.3
COW 8 W	28.6	29.3	4.0	15.8	35.2
COW 40 W	30.1	29.8	2.0	27.1	33.7

Table 90. Royal terrace PUSCH statistics for a TCP uplink data flow.

Coverage Combination	Mean PUSCH (Mb/s)	Median PUSCH (Mb/s)	Standard Deviation (Mb/s)	Min PUSCH (Mb/s)	Max PUSCH (Mb/s)
PSCR MN	6.2	6.1	2.9	2.4	11.8
COW 8 W	17.7	18.0	0.8	14.8	18.7
COW 40 W	17.8	18.3	1.1	15.2	19.2

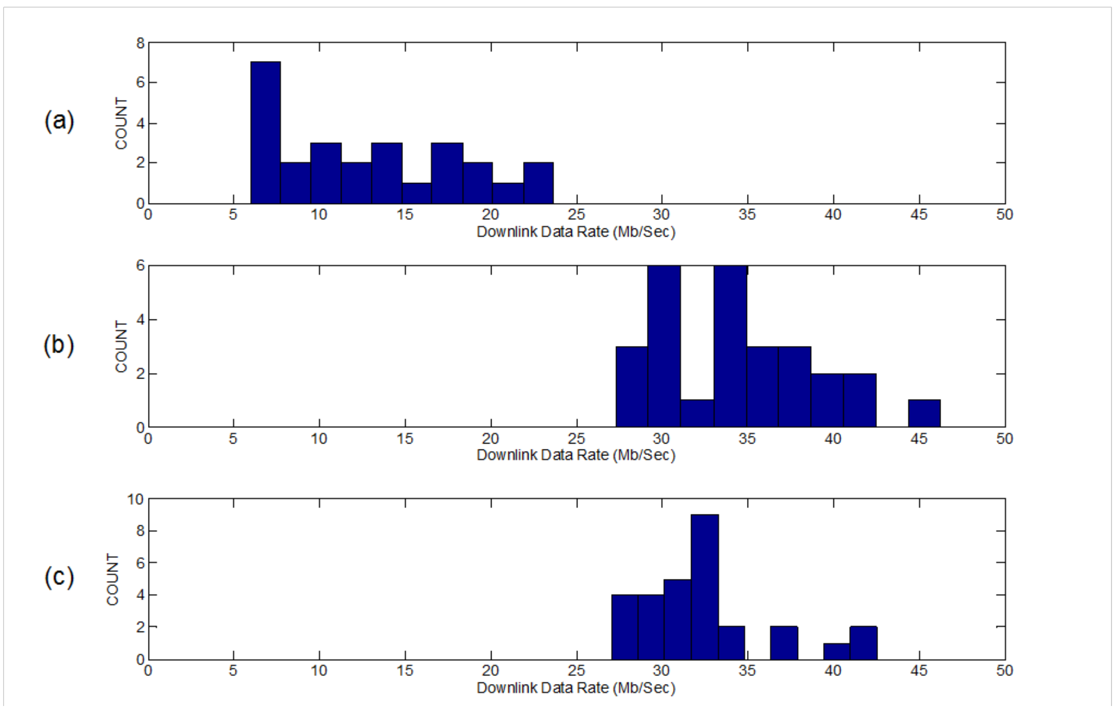

Figure 158. Royal Terrace histograms of serving cell PDSCH for different coverage combinations with a UDP downlink data flow, (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W.

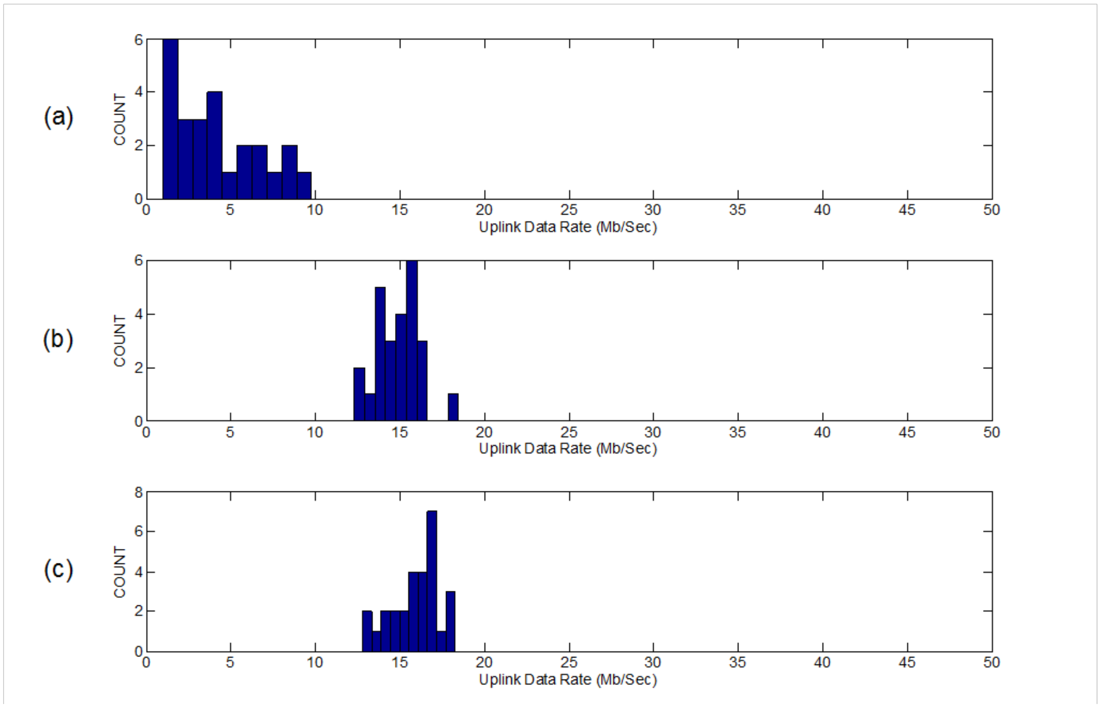

Figure 159. Royal Terrace histograms of serving cell PUSCH for different coverage combinations with a UDP uplink data flow, (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W.

Table 91. Royal terrace PDSCH statistics for a UDP downlink data flow.

Coverage Combination	**Mean PDSCH (Mb/s)**	**Median PDSCH (Mb/s)**	**Standard Deviation (Mb/s)**	**Min PDSCH (Mb/s)**	**Max PDSCH (Mb/s)**
PSCR MN	12.8	11.5	5.5	6.0	23.7
COW 8 W	34.5	34.3	4.7	27.3	46.3
COW 40 W	32.6	31.9	3.9	27.1	42.5

Table 92. Royal terrace PUSCH statistics for a UDP uplink data flow.

Coverage Combination	**Mean PDSCH (Mb/s)**	**Median PDSCH (Mb/s)**	**Standard Deviation (Mb/s)**	**Min PDSCH (Mb/s)**	**Max PDSCH (Mb/s)**
PSCR MN	4.2	3.7	2.6	1.0	9.8
COW 8 W	14.9	15.0	1.4	12.3	18.5
COW 40 W	16.0	16.2	1.4	12.8	18.3

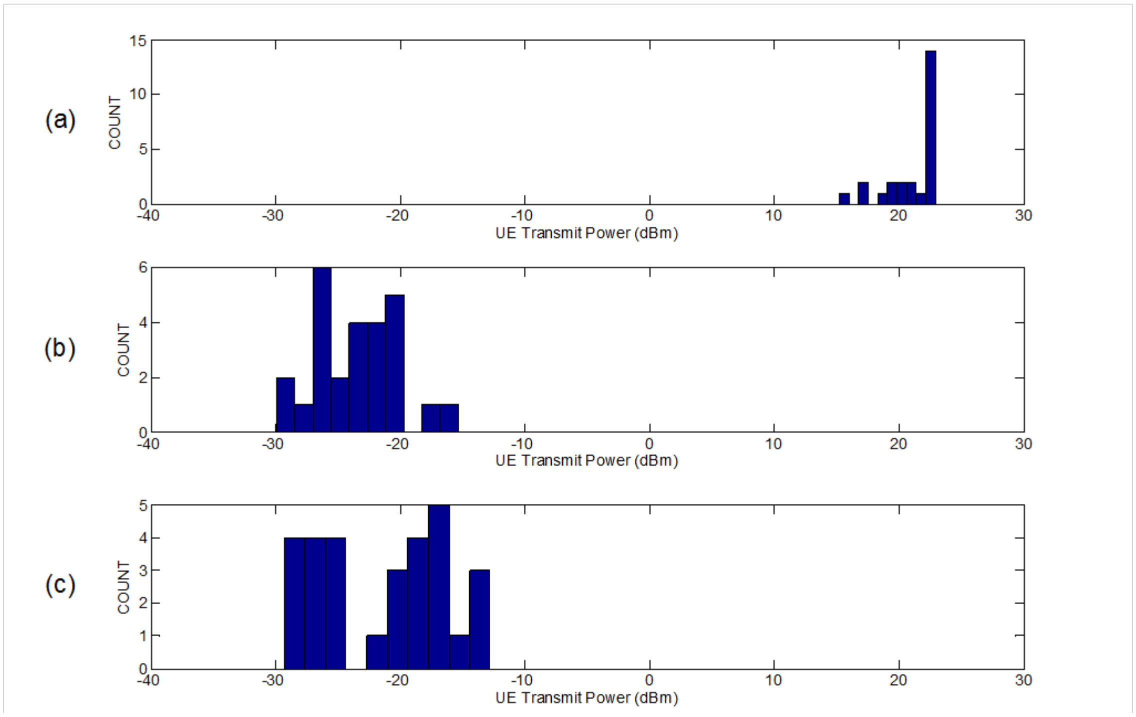

Figure 160. Royal Terrace histograms of UE transmit power for different coverage combinations with a TCP downlink data flow, (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W.

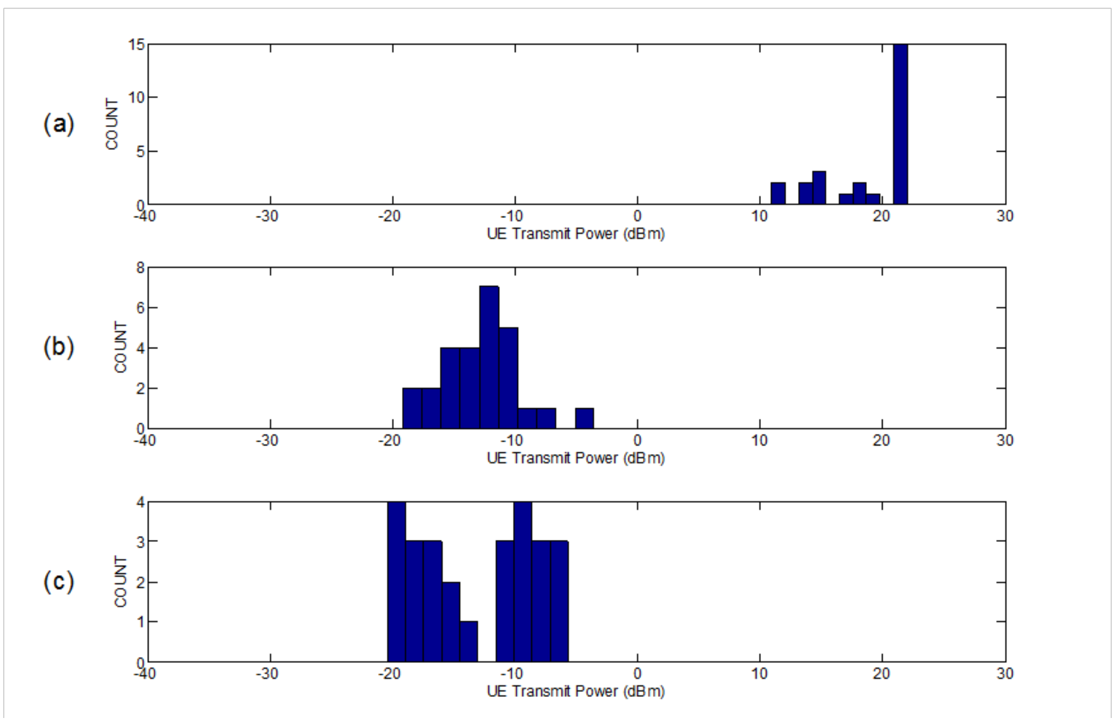

Figure 161. Royal Terrace histograms of UE transmit power for different coverage combinations with a TCP uplink data flow, (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W.

Table 93. Royal Terrace UE transmit power statistics for a TCP downlink data flow.

Coverage Combination	**Mean UEpwr (dBm)**	**Median UEpwr (dBm)**	**Standard Deviation (dBm)**	**Min UEpwr (dBm)**	**Max UEpwr (dBm)**
PSCR MN	21.1	22.4	2.2	15.2	23.0
COW 8 W	-23.6	-23.8	3.5	-30.0	-15.4
COW 40 W	-21.6	-20.6	5.1	-29.3	-12.8

Table 94. Royal Terrace UE transmit power statistics for a TCP uplink data flow.

Coverage Combination	**Mean UEpwr (dBm)**	**Median UEpwr (dBm)**	**Standard Deviation (dBm)**	**Min UEpwr (dBm)**	**Max UEpwr (dBm)**
PSCR MN	19.0	21.7	3.8	10.9	22
COW 8 W	-12.8	-12.8	3.2	-19.2	-3.6
COW 40 W	-13.3	-12.1	5.1	-20.5	-5.7

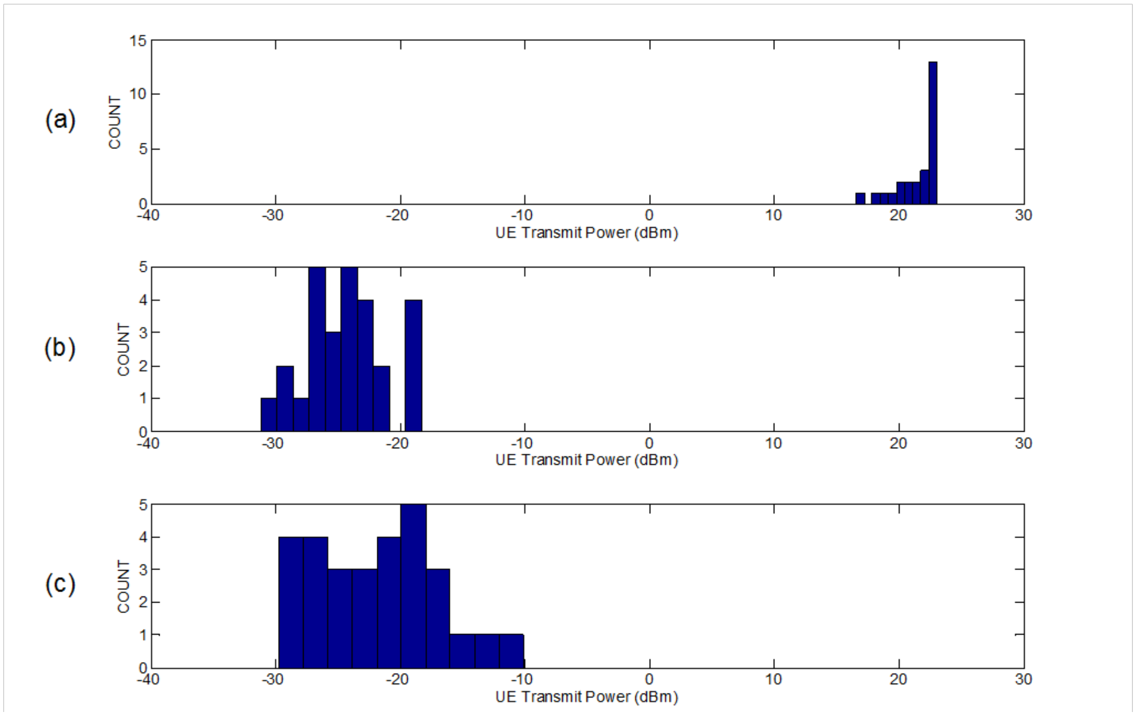

Figure 162. Royal Terrace histograms of serving cell transmit power for different coverage combinations with a UDP downlink data flow, (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W.

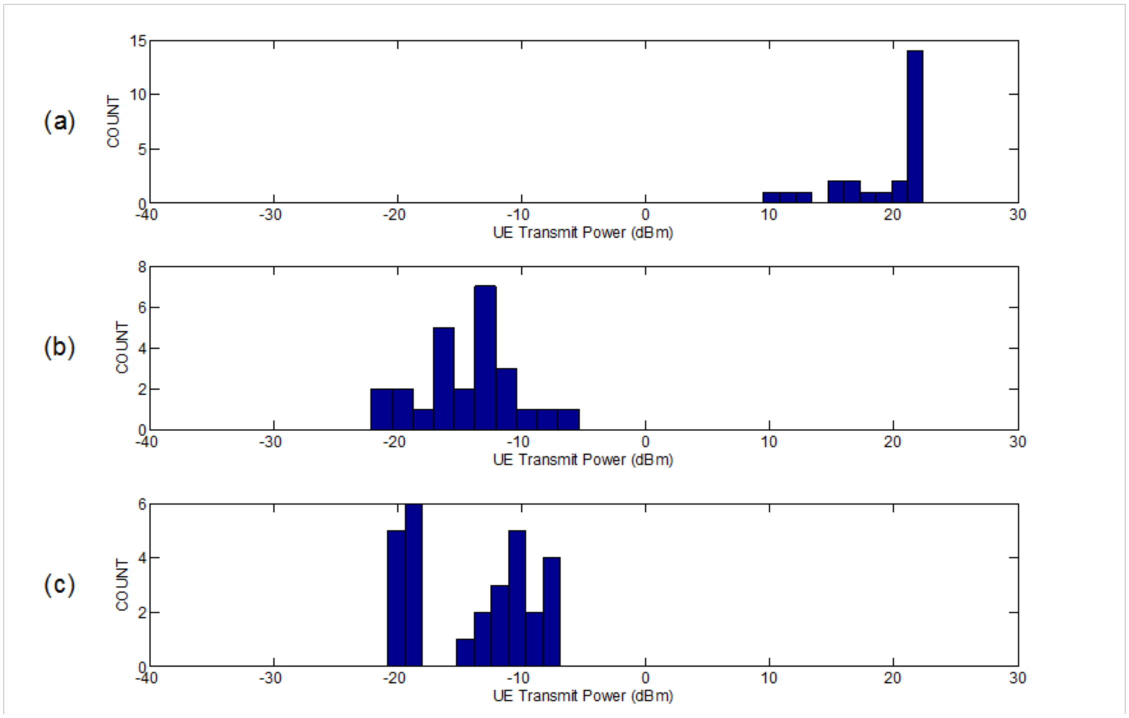

Figure 163. Royal Terrace histograms of serving cell transmit power for different coverage combinations with a UDP uplink data flow, (a) PSCR MN, (b) COW at 8 W, (c) COW at 40 W.

Table 95. Royal Terrace UE transmit power statistics for a UDP downlink data flow.

Coverage Combination	Mean UEpwr (dBm)	Median UEpwr (dBm)	Standard Deviation (dBm)	Min UEpwr (dBm)	Max UEpwr (dBm)
PSCR MN	21.5	22.4	1.7	16.6	23.0
COW 8 W	-24.3	-24.5	3.3	-31.2	-18.3
COW 40 W	-21.9	-21.7	5.0	-29.7	-10.1

Table 96. Royal Terrace UE transmit power statistics for a UDP uplink data flow.

Coverage Combination	Mean UEpwr (dBm)	Median UEpwr (dBm)	Standard Deviation (dBm)	Min UEpwr (dBm)	Max UEpwr (dBm)
PSCR MN	19.3	22.0	3.8	9.5	22.4
COW 8 W	-14.4	-13.6	4.0	-22.2	-5.4
COW 40 W	-13.9	-12.2	4.8	-20.8	-6.9

4. COORS EVENT CENTER

The Coors Event Center (CEC), depicted in Figure 164, is a multi-functional facility located on the campus of the University of Colorado. The CEC hosts a wide variety of events such as graduation ceremonies, final examinations, sporting events, and celebrity appearances. The stadium portion the CEC was originally built in 1979 and it seats approximately 11,000 people. Figure 165 depicts the interior of the CEC stadium during a college basketball game. The facilities and office section was completed in 2010 and greatly enhanced the utility of CEC. This section contains basketball and volleyball courts, a weight training room, a sports medicine facility, a television studio, numerous offices, and storage areas.

Both sections of the CEC are constructed of steel and concrete. The stadium has no windows and it has numerous metal-door entry points around the perimeter. These characteristics provide a relatively high level of shielding from radio signals from the outside. The facilities/office section (FOS) does contain numerous windows, but these are also the low-emissivity type (low-E), which significantly reduce Band 14 LTE signal levels. The CEC as a whole is well shielded and it provides a significant challenge for public safety communications.

Figure 164. Aerial view of the Coors Event Center showing both the stadium and facilities/offices sections (FOS).

Figure 165. Interior view of the CEC stadium hosting a basketball game.

4.1 Walk Test Routes

Walk tests were performed over four interior walk paths:

- Around the outer circumference of the upper stadium concourse
- A route ranging from the upper concourse to the stadium floor
- A route encompassing level 2 of the infrastructure/offices section
- A route covering critical areas of lowest level (level 1) of the infrastructure/offices section

We also performed tests over two routes outside the CEC. The first route was on the ground level along the north side of the CEC, and the second covered a 270 degree sector along the west, south, and east sections of the CEC. We performed outdoor measurements in order to: 1) study exterior RF signal levels and 2) assess building leakage levels.

The stadium walk routes are shown in Figures 166 and 167. The first walk route covers a closed circuit around the upper perimeter of the stadium concourse. This level contains a number of entrances to the CEC. The concourse also provides easy access to the seating area. The first route is depicted in Figure 166, and it consists of 10 waypoints. The route starts at the north end of the stadium concourse and it progresses in a counter clockwise direction.

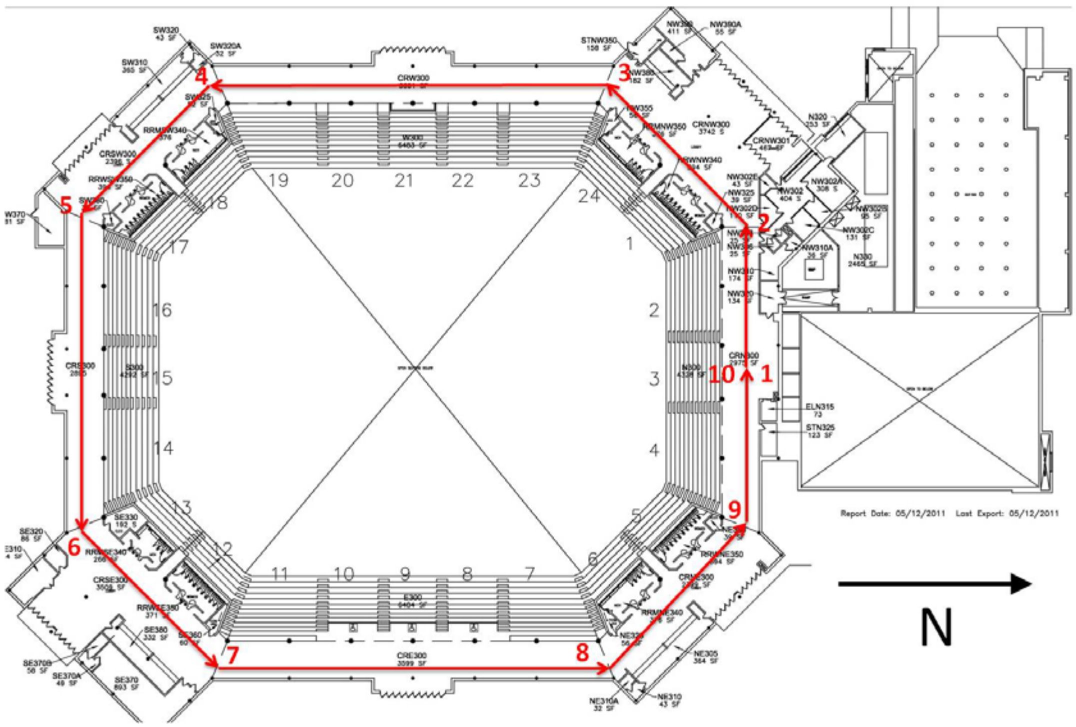

Figure 166. The upper walk route around the upper concourse of the CEC. The navigation way pints are numbered sequentially 1–10.

The seating area walk route is shown in Figure 167. This route is more complex, and it traverses a closed circuit. It contains a total of 15 navigation way points. This route starts on the upper concourse, adjacent to the NW entrance, and it descends down a series of steps to the floor of the stadium. The route then progresses along a clockwise circuit around the perimeter of the stadium floor and through the seating area back to the starting point. This walk path evaluates the LTE system performance variability as a function of elevation from the stadium concourse down to the main floor.

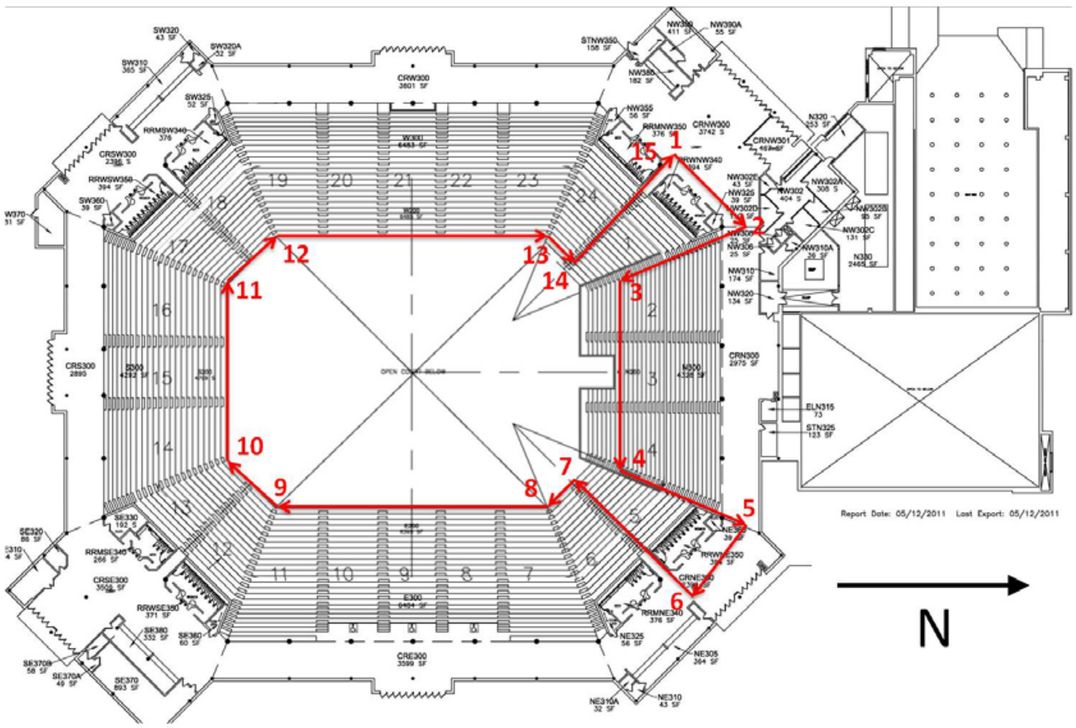

Figure 167. The seating area/stadium floor walk route in the CEC. The navigation way points are numbered sequentially 1–15.

The next series of walk routes are located in the FOS, on the north side of the CEC. The infrastructure area contains two levels. Level 1 is located at approximately the same height as the parking spaces shown in Figure 164. The level 1 walk route is shown in Figure 168. It contains 15 navigation way points. The walk starts near the main access stairs and progresses to an entrance that is adjacent to the north parking lot (way point #2). The walk path then swings past the starting point and progresses in a southerly direction and reaches the entrance to the stadium floor (way point #6) . It then progresses deep into the core of the building. This section contains numerous offices and a sports medicine facility. The route then continues on a closed circuit until the starting point is reached once again. This part of the FOS presents significant challenges for radio communications

The walk route on the first floor of the FOS is shown in Figure 168. This is the most complex route, and it contains a total of 23 navigation way points. The starting point is located at the Regent Drive entrance, located on the northwest side of the building. The route initially progresses in an easterly direction past a practice gym and into the main administrative offices section (way points 1–7). The route then continues in a southwesterly direction past a weight training facility and back through the administrative offices section (way points 8–17). It then continues on a closed circuit back to the entrance (way points 18–23).

The two outdoor walk routes are shown in Figures 170 and 171. The purpose of these paths is to measure RF signal levels external to the building and also to measure leakage from the inside to the outside of the building produced by the SCDA deployment inside the CEC stadium (described in Section 4.3).

The first walk route is located on the upper level plaza that provides the main access to the stadium. This route starts near the ticketing sales windows and progresses around the south end of the CEC and terminates on the northeast side near the tennis courts. The route consists of seven navigation waypoints and covers an angular sector of approximately 270 degrees. The second walk route traverses the north side of the CEC. This path begins on the street level near the northwest entrance and progresses along a sidewalk to a point near the northeastern corner of the FOS.

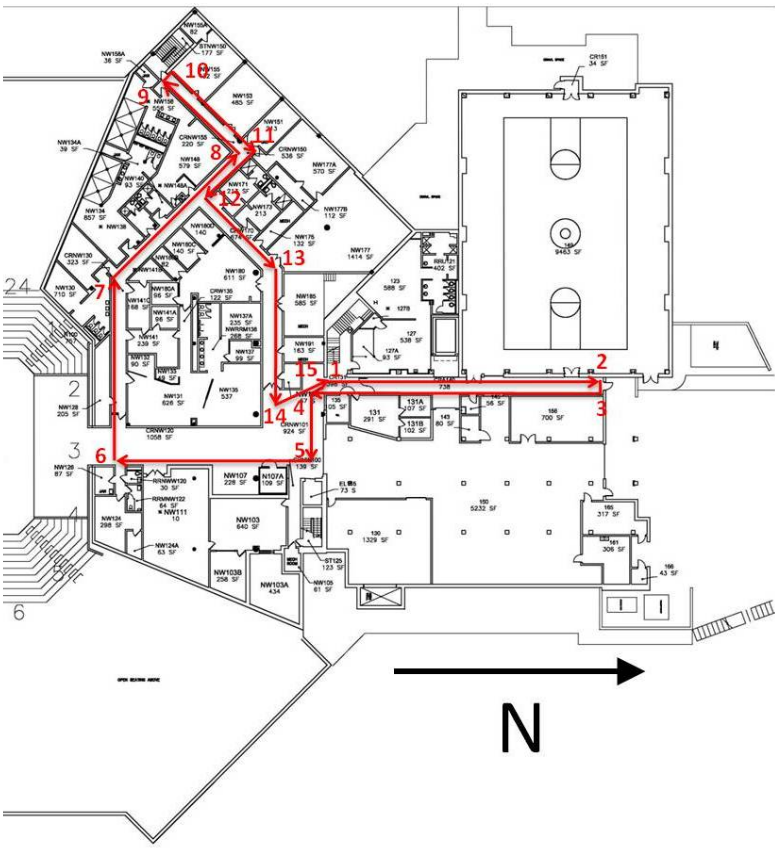

Figure 168. Level 1 walk route at the CEC. The navigation way points are sequentially numbered 1–15.

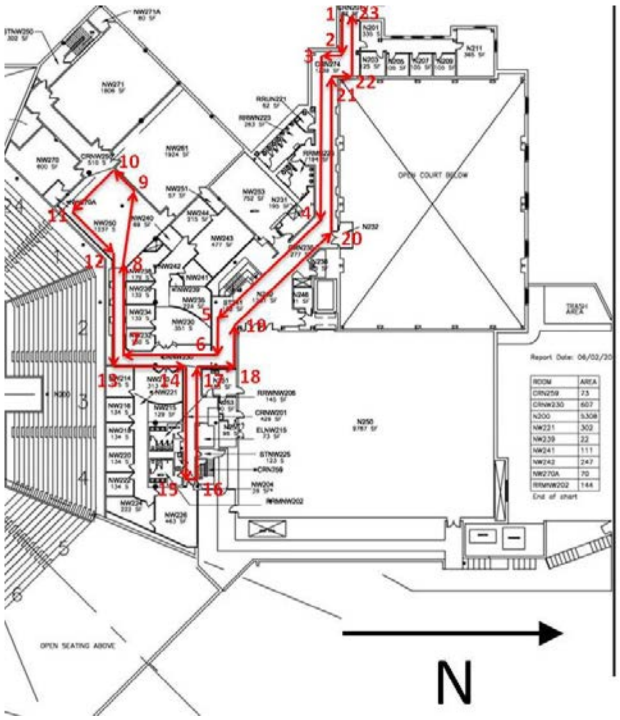

Figure 169. The level 2 walk route at the CEC. The navigation way points are numbered sequentially 1–23.

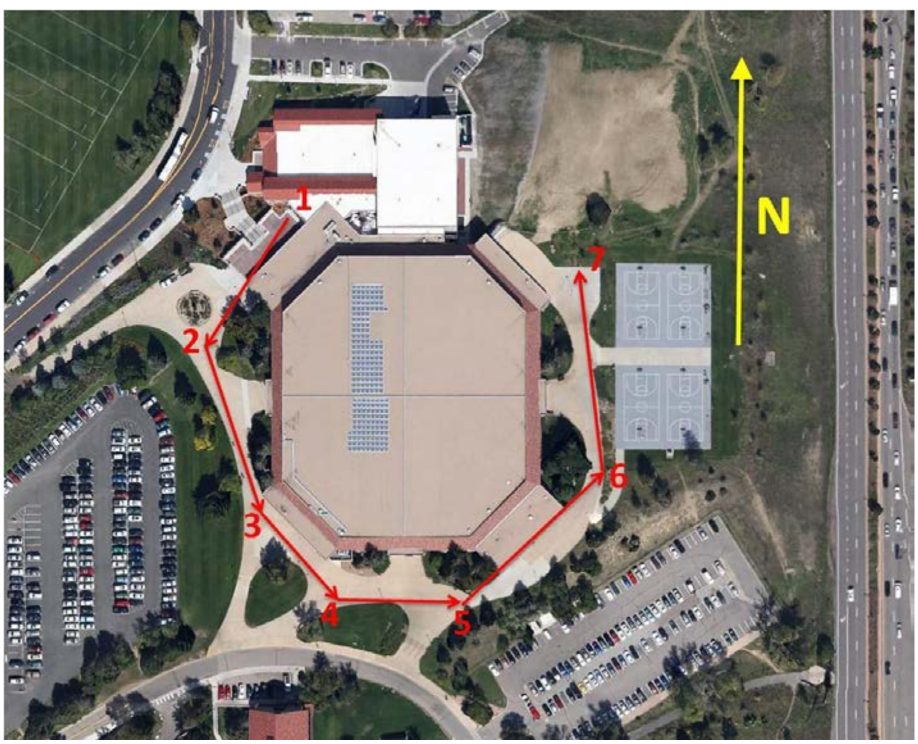

Figure 170. First outside walk route around the upper level of the CEC. The navigation way points are numbered sequentially 1–7. Regent drive is located in the upper left corner and Highway 36 (28th Street) is located on the right side of the figure.

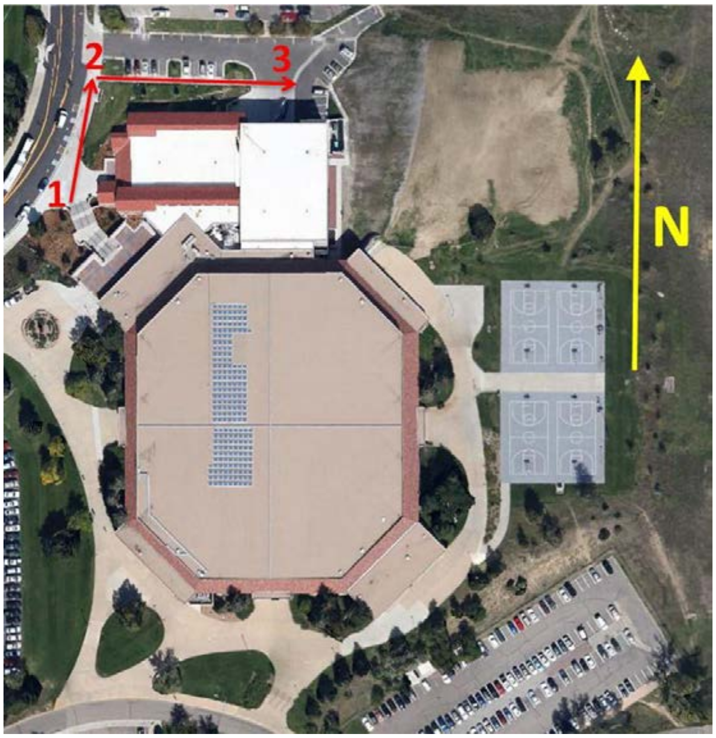

Figure 171. Second outside walk route on the north side of the CEC. The navigation way points are numbered sequentially 1–3.

4.2 Measurement Program

The measurement campaign conducted at the CEC was similar in scope to that at the DLC. We performed a series of walk tests both inside and outside the CEC. We performed tests for a number of different RF coverage configurations that involved the PSCR MN, a cell on wheels (COW) and an SCDA deployed in the stadium. We used the backpack system (see Section 2.2) to perform the walk testing.

We performed tests using the following progression of RF coverage:

- PSCR MN only
- COW at 40 W
- COW at 40 W and PSCR MN
- PSCR MN + COW at 40 W
- SCDA at 1 W
- SCDA at 1 W + COW at 40 W
- SCDA at 1 W + COW at 40 W + PSCR
- SCDA at 5 W + COW at 40 W

The test procedures were almost identical to those described in the in-building test plan [6], except that the downlink and uplink data flows were limited to the user datagram protocol

(UDP). We made this choice to save time (due to heavy usage of the CEC for various functions) and to ensure that a wide range of RF coverage options could be investigated.

4.3 Radio-Frequency Coverage of the Coors Event Center

The CEC presents a significant challenge for public safety wireless communications due to its steel and concrete construction. We examined the ability of Band 14 LTE signals to provide interior coverage for the following deployments:

- The PSCR MN
- COW positioned in the parking lot just north of the CEC
- The SCDA placed in the catwalk above the stadium floor
- A number of coverage configurations based on combinations of the PSCR MN, COW, and SCDA.

4.3.1 PSCR Macro Network

The configuration of the PSCR MN used for the CEC tests is shown in Figure 172. The Green Mountain eNB was the only active station for these tests, and it is located 1.9 km southwest of the CEC. We used only one active eNB for this testing instead of both the Green Mountain and Table Mountain eNBs because our DLC results indicated that the influence of the Table Mountain station was minimal due to its distance from the testing location. The Green Mountain station was set at a nominal power transmission level of 40 W throughout the CEC testing.

Figure 172. The PSCR MN configuration used for testing at the CEC.

4.3.2 Cell on Wheels (COW)

The PSCR COW was positioned in a parking lot at a location 80 m from the north wall of the FOS as is shown in Figure 173. Figures 173 and 174 both show photos of the COW deployment. The eNB was set at a nominal power level of 40 W which was fed directly to a cellular antenna that was bore sighted at the north wall of the CEC. The standoff distance of 80 m ensured complete coverage of the CEC with the 65 degree antenna beamwidth. Since there was a line-of-sight condition between the COW and the Green Mountain eNB, microwave backhaul was used to connect the COW to a companion system located on Green Mountain. This system, in turn, was connected the PSCR network and the evolved packet core located back at the Department of Commerce Boulder Labs. Electric power was provided by an on-board gasoline-powered generator with ample capacity to handle a full day of testing.

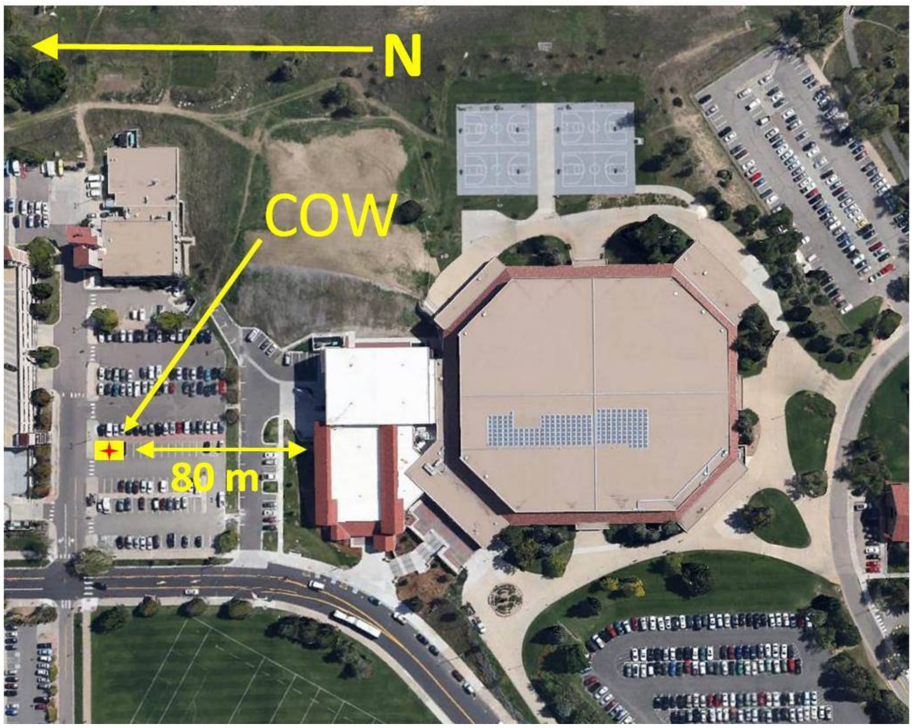

Figure 173. Aerial view of the COW deployment at the CEC. The COW is located 80 m from the north wall of the CEC.

Figure 174. The COW deployment viewed from the north. The COW antenna is bore sighted directly at the north wall of the CEC.

Figure 175. The COW deployment viewed from the west. The dish antenna is the microwave backhaul and it is aimed directly at the Green Mountain eNB, where the companion link system is located.

4.3.3 Small-Cell Deployment in the CEC

PSCR engineers installed a Band 14 small cell in the CEC stadium area in order to improve in-building coverage. The small cell was installed on a catwalk high above the stadium and the approximate location is annotated in Figures 176 and 177. The small cell and a backhaul router were mounted to a custom-engineered metal plate which, in turn, was securely fastened to the catwalk railing. The deployment is depicted in Figures 178 and 179. The small cell fed two COTS Band 14 antennas which were mounted on the top of the catwalk railing and spaced 3 m apart. The small-cell power supply was mounted to the railing using a similar metal plate fastening arrangement.

A microwave link was used to establish backhaul to the EPC back at the PSCR labs. A microwave dish and associated transceiver was set up on the roof and its bore sighted at a companion unit located at the Green mountain eNB. The roof installation is shown in Figure 180. The microwave link was connected to the small cell through the router using a power over Ethernet connection (POE) as is shown in Figures 179 and 181.

The small cell was typically operated at a power level of 1 W for the majority of the tests. This power level was more than sufficient to provide coverage in the stadium area. The power level was increased to 5 W on a special test of signal penetration into the infrastructure section of the CEC.

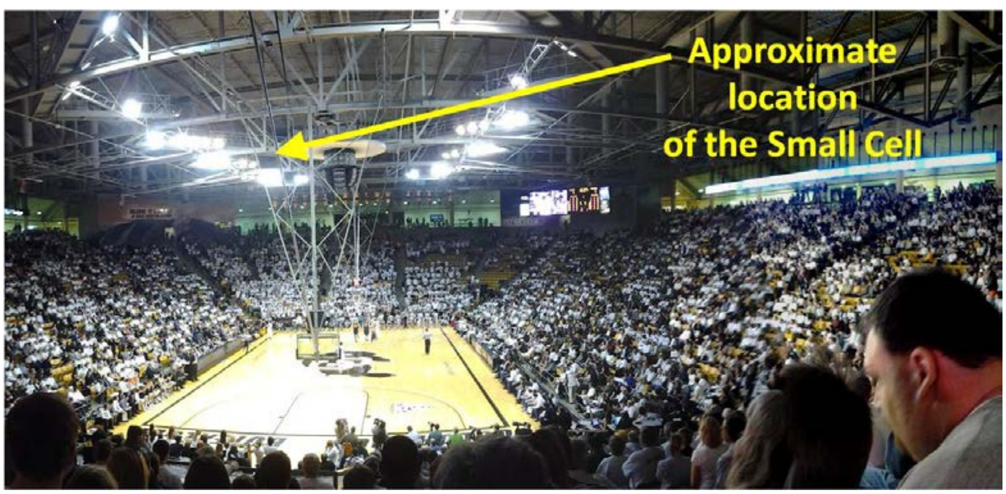

Figure 176. Approximate location of the small cell (not deployed in this photo) as viewed from the north end of the stadium.

Figure 177. Approximate location of the small cell as viewed from the outside.

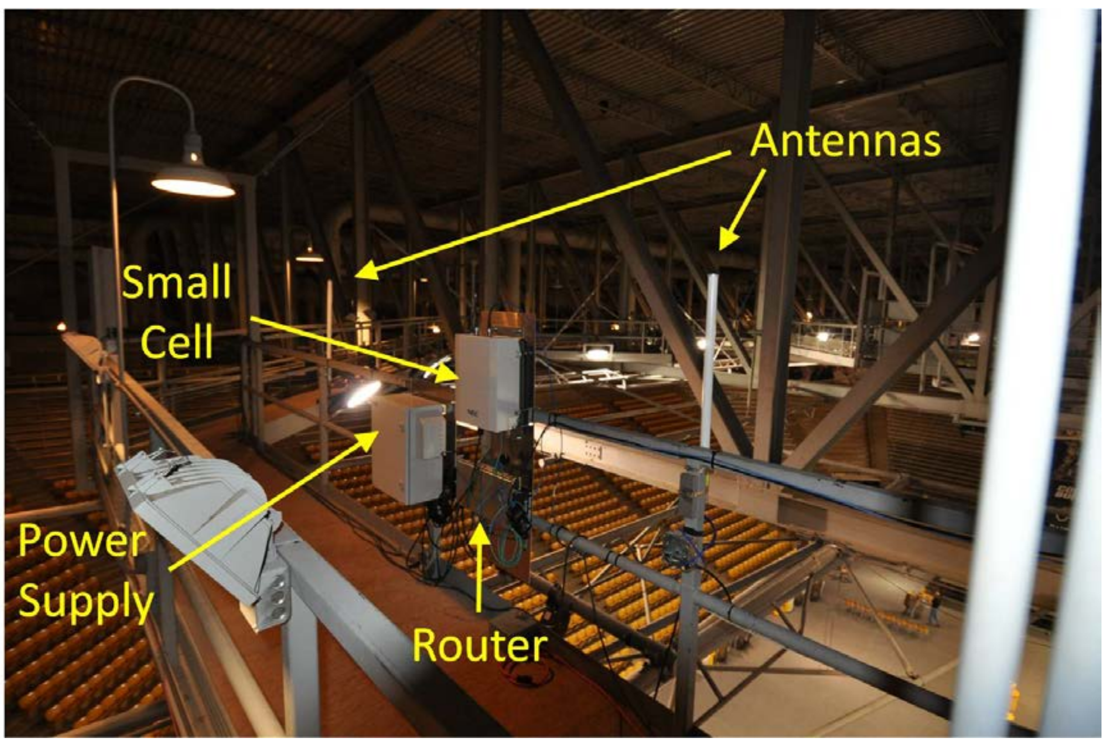

Figure 178. Small cell deployment on a catwalk above the CEC stadium.

Figure 179. A PSCR engineer installs power over Ethernet cable from the microwave backhaul to the router.

Figure 180. Microwave backhaul antenna and transceiver bore sighted at the Green Mountain station.

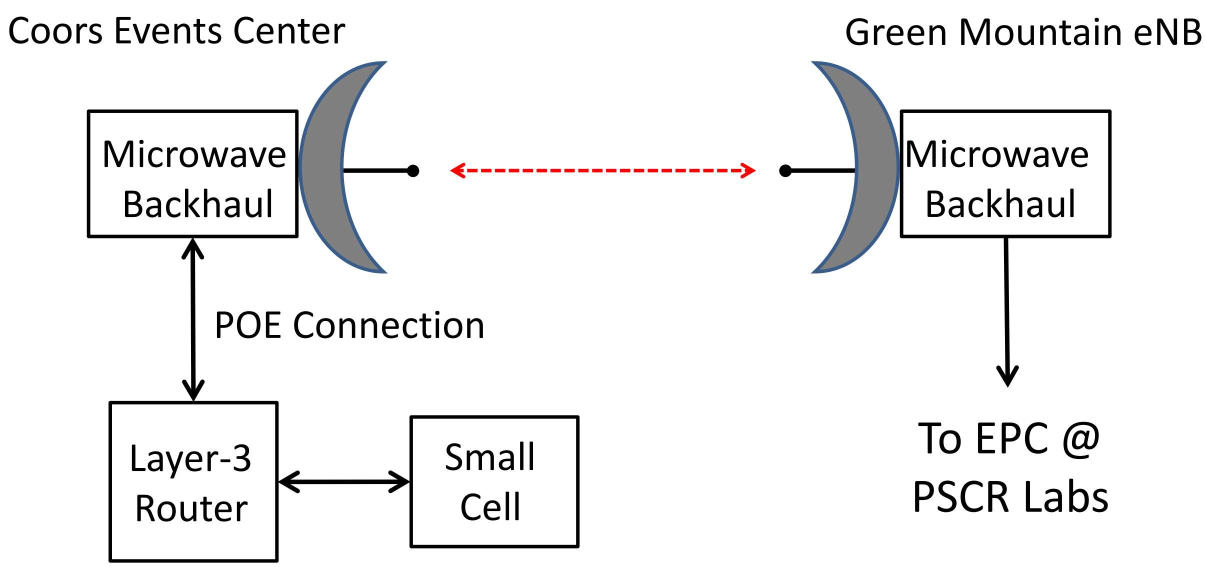

Figure 181. Schematic of the microwave backhaul system between the CEC and PSCR labs.

5. CEC MEASURED RESULTS

We performed measurements using the backpack system that was used for the earlier DLC measurements (see Section 2.2). Indoor measurements were performed in the stadium area of the CEC as well as on the two levels of the FOS using either six or seven different coverage combinations. Walk tests were also performed for two outside walk routes. The strategic approach here is to provide a side-by-side comparison of selected LTE parameters for different coverage configurations for each walk path.

Once again, we transmitted both uplink and downlink data over the radio link between the UE in the backpack measurement system and the serving eNB. The Netperf software package was used to generate data transfers using the same procedures as in the DLC measurements [6].

Because of the large number of LTE parameters and coverage combinations, we present CEC results only for the following LTE parameters:

- Reference signal received power (RSRP)
- Carrier to interference and noise ratio (CINR)
- Physical downlink shared channel (PDSCH) data throughput rates
- Physical uplink shared channel (PUSCH) data throughput rates
- UE transmitted power

5.1 CEC Stadium Measured Results

The longest walk paths occurred in the stadium area. We present the combined results of the upper and lower walk paths of Figures 166 and 167. We performed measurements in the stadium for the following six coverage combinations:

- PSCR MN only at 40 W
- COW only at 40 W
- COW at 40 W + PSCR MN
- SCDA only at 1 W
- SCDA at 1W + COW at 40 W
- SCDA at 1W + COW at 40 W + PSCR MN

The RSRP results for a UDP downlink data flow are shown in Figures 182–187 for the six coverage combinations. Histograms for the RSRP for both UDP downlink and uplink data flows are provided in Figures 188 and 189, and the associated summary statistics are given in Tables 97 and 98.

A study of Figure 182 shows that the PSCR MN provides the best coverage on both the west and south sides of CEC. This is caused by the combination of the Green Mountain eNB being located southwest of the CEC and leakage through the doors on the west and south entrances.

The worst coverage occurs on the upper concourse on the northwest corner of the CEC, which is caused by blockage effects of an interior wall at the top of the seating section. This coverage problem is remedied through use of the COW, which significantly improves coverage on the north side of the CEC as can be seen in Figure 183. The COW also provides improved coverage on the south side of the stadium. The overall improvement in signal levels over the PSCR MN is approximately 8 dB with the COW.

The combination of the COW and the PSCR MN provides an additional coverage improvement on the south side of the CEC. This result is reasonable since the macro network coverage is strongest on the south and west portions of the CEC. The stadium coverage significantly improves when the SCDA system is operated at 1 W. Typical median signal levels increase more than 25 dB over that of the PSCR MN. When both the COW and the PSCR MN are added to the SCDA coverage, the RSRP results do not change much—clearly the SCDA is the dominant stadium coverage element.

The CINR results for downlink and uplink data flows are illustrated in Figures 190 and 191 respectively. Summary statistics are provided in Tables 99 and 100. The observed trends as a function of coverage track those seen in the RSRP results. The COW provides a noticeable improvement in signal-to-noise performance. The median CINR level increases over the corresponding PSCR MN results are 6 dB for a downlink data flow and almost 10 dB for an uplink data flow. The best overall CINR results occur when the SCDA system provides coverage—no surprise here. Relative to the PSCR MN, the SCDA yields an improvement of 12 dB in the median value of CINR for both downlink and uplink data flows. When the SCDA is used in combination with the COW, the range of data values increases due to neighbor cell interference.

The PDSCH downlink data rates are shown in Figure 192 and summary statistics are provided in Table 101. The PSCR MN provides good data rates over much of the walk path. A median downlink data rate of 23 Mb/s is seen. We see a peak value of 38 Mb/s. When the COW provides coverage, there is an increase in data rates with peak values of 46 Mb/s. When the COW and macro network provide combined coverage, there are increased occurrences of reduced data rates due to handovers that occur between the COW and the macro network in the south end of the stadium. Once again, increased RF coverage does not translate into improved data rates. A careful network optimization would be required to correct this.

The best overall results are obtained with coverage provided by the SCDA, with a median downlink data rate of 41 Mb/s and peak value of more than 50 Mb/s. We see degraded results when the COW is added to the coverage due to handovers between the SCDA and the COW on the north side of the stadium. The situation remains approximately the same when the PSCR MN is added to the coverage and similar distributions of data rates occur.

The PUSCH uplink data rates are given in Figure 193. Associated statistical summaries are provided in Table 102. There is a high count of low data rates when coverage is provided by the PSCR MN. In this case we see a median uplink data rate of 4 Mb/s and a peak rate of 15 Mb/s. This is attributed to the combination of low UE transmit power and high path losses. The situation improves when the COW provides coverage and higher data rates occur, with a median value of 12 Mb/s and a peak of 16 Mb/s. Adding the macro network generates more occurences of reduced data rates, which is caused by COW/macro network handovers on the concourse at the south end of the stadium. We see somewhat degraded results, relative to those of the COW, when the SCDA system is providing in-building coverage, with a median uplink data rate of 10 Mb/s and a peak value of 14 Mb/s. Our tests indicate this effect may be caused by some high signal level issues with the UE, due to deployment in close proximity to the SCDA. Similar uplink data rate results are seen when the COW and macro network are added to the in-building coverage.

The UE transmit power histograms are plotted in Figures 194 and 195 as a function of coverage for both UDP downlink and uplink data flows. Key statistics are compiled in Tables 103 and 104. As expected, we see high counts of UE transmit power levels greater than 20 dBm when the PSCR MN provides coverage, with a median value of 22 dBm and a peak level of 23 dBm for both downlink and uplink data flows. These results are caused by the high path losses between the UE and the serving eNB on Green Mountain.

When the COW provides coverage, we see significantly reduced power levels. For downlink data flows, we obtain a median value of 3 dBm and a peak of 17 dBm. We see less of an improvement for uplink data flows, which is attributed to the increased data payload; the median and peak values are 11 dBm and 22 dBm, respectively. The best overall performance is seen when the SCDA system is providing in-building performance or when it is used in combination with the other coverage systems. The improvements are quite pronounced for both downlink and uplink data flows. For a downlink data flow, we see median and peak values of −38 dBm and −21dBm respectively. In the uplink case we see an upward shift with a median of −16 dBm and a peak value of 9 dBm—due to a heavier data payload.

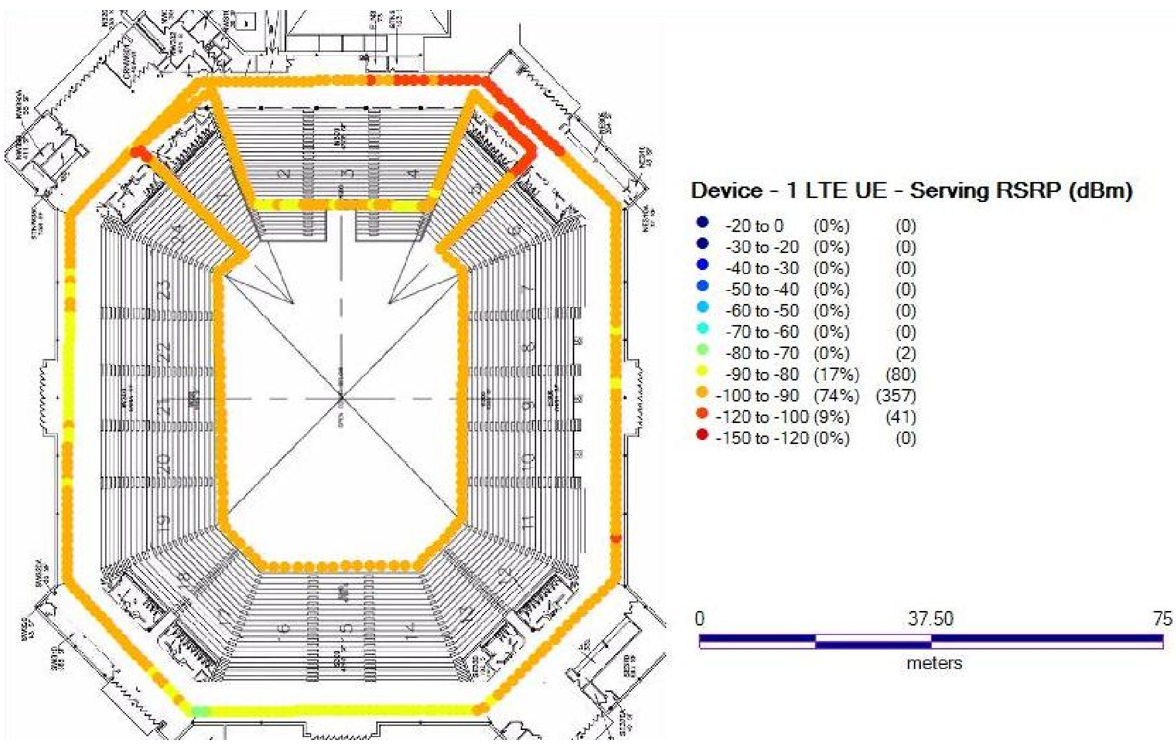

Figure 182. CEC Stadium reference signal received power (RSRP) for a UDP downlink data flow with the PSCR MN at 40 W. North is at the top of the figure.

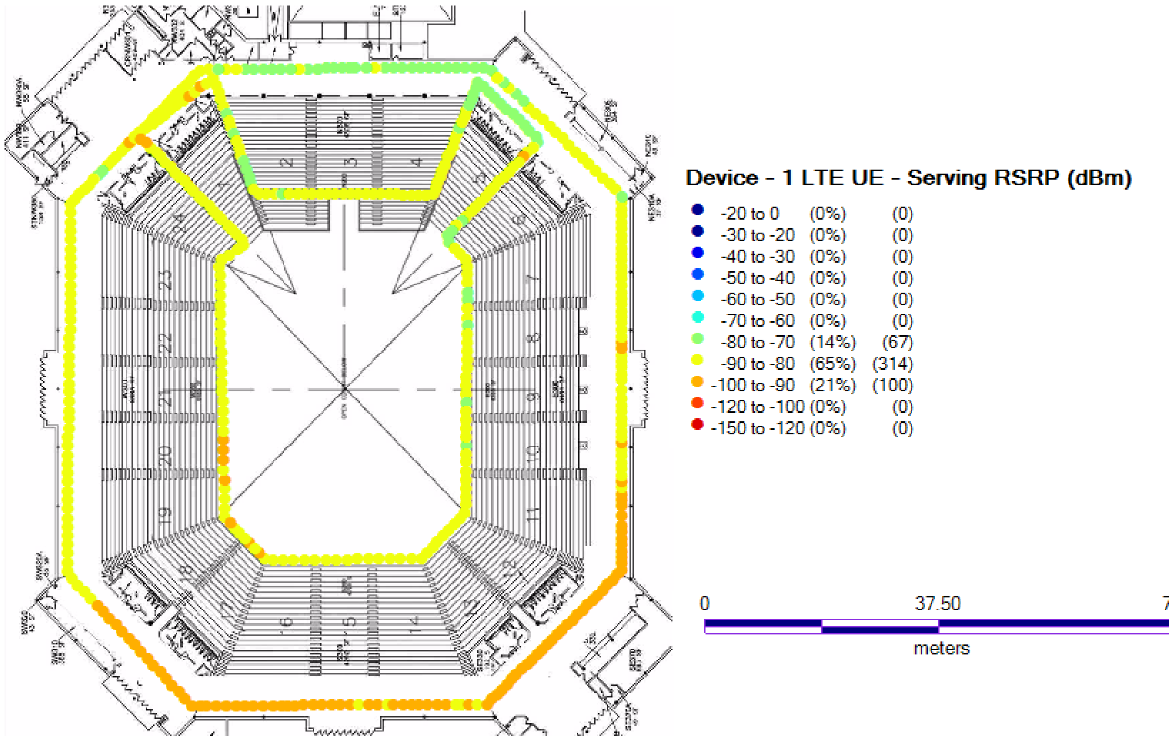

Figure 183. CEC Stadium reference signal received power (RSRP) for a UDP downlink data flow with the COW transmitting at 40 W. North is at the top of the figure.

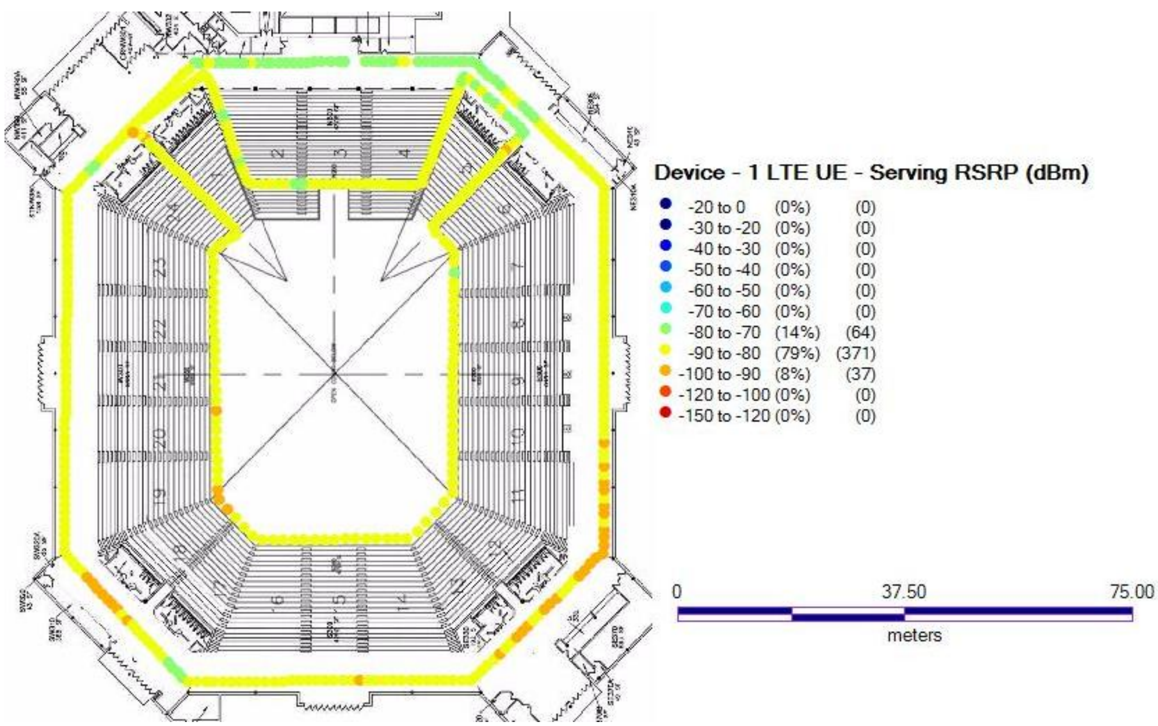

Figure 184. CEC Stadium reference signal received power (RSRP) for a UDP downlink data flow with the COW transmitting at 40 W and the PSCR MN. North is at the top of the figure.

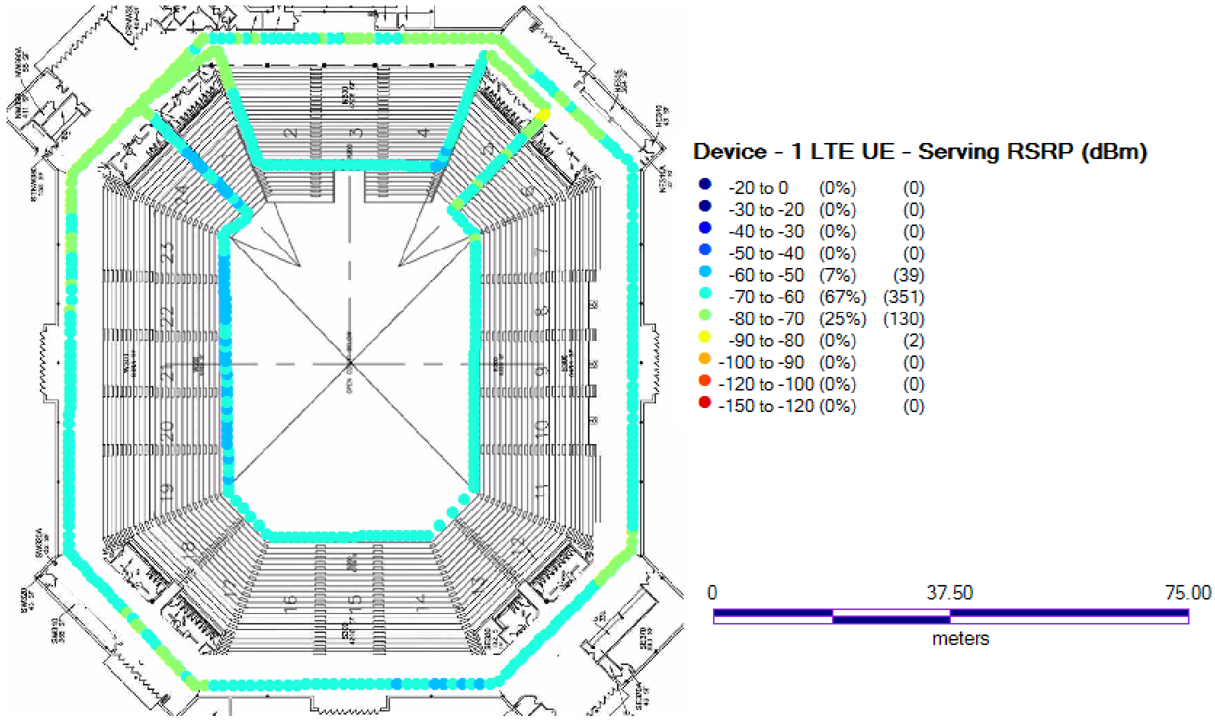

Figure 185. CEC Stadium reference signal received power (RSRP) for a UDP downlink data flow with the SCDA at 1 W. North is at the top of the figure.

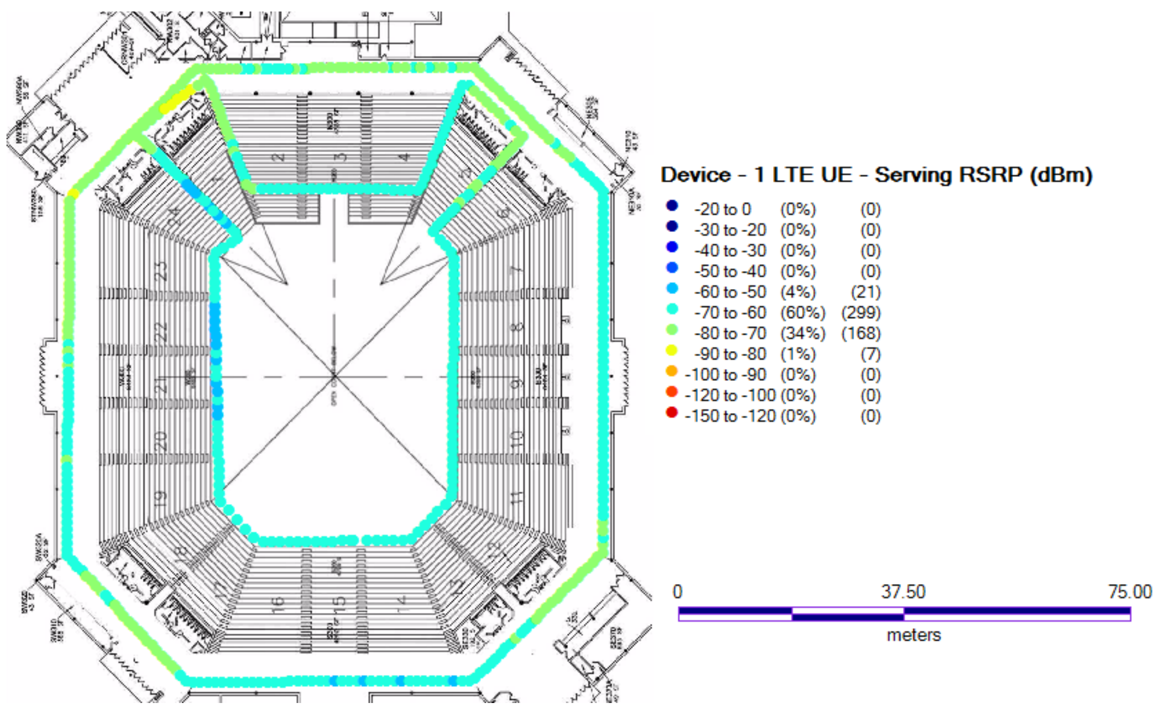

Figure 186. CEC Stadium reference signal received power (RSRP) for a UDP downlink data flow with the SCDA at 1 W and the COW at 40 W. North is at the top of the figure.

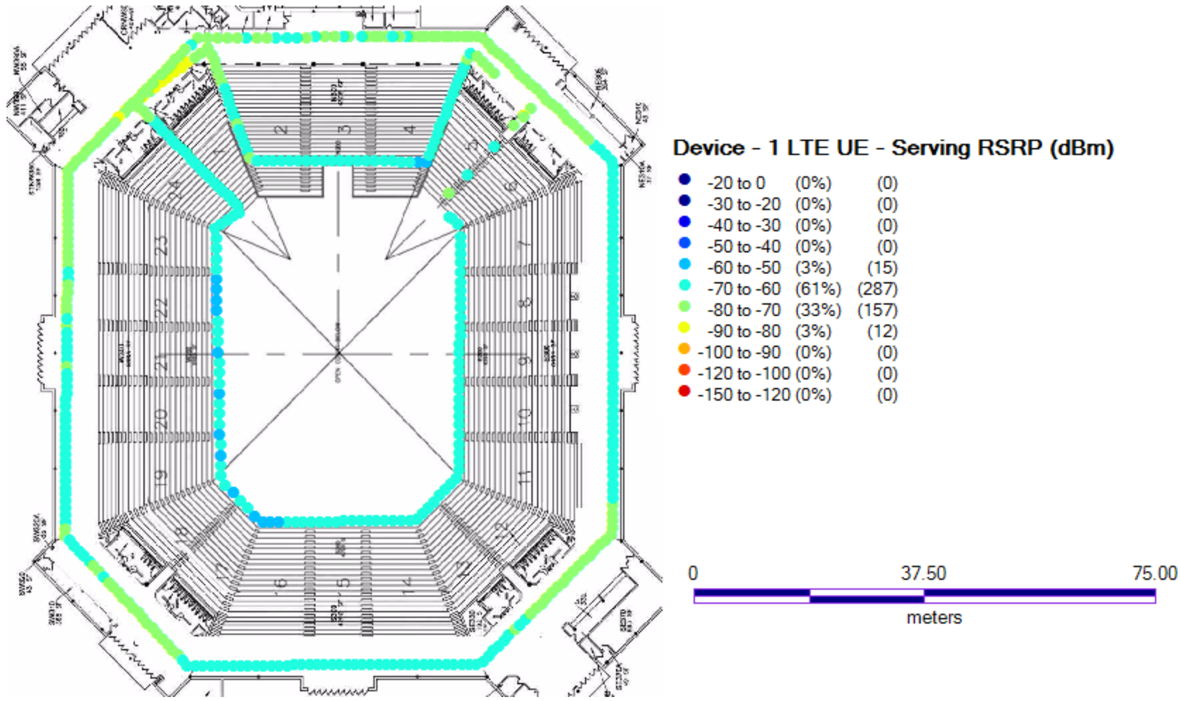

Figure 187. CEC Stadium reference signal received power (RSRP) for a UDP downlink data flow with the SCDA at 1 W and the PSCR MN. North is at the top of the figure.

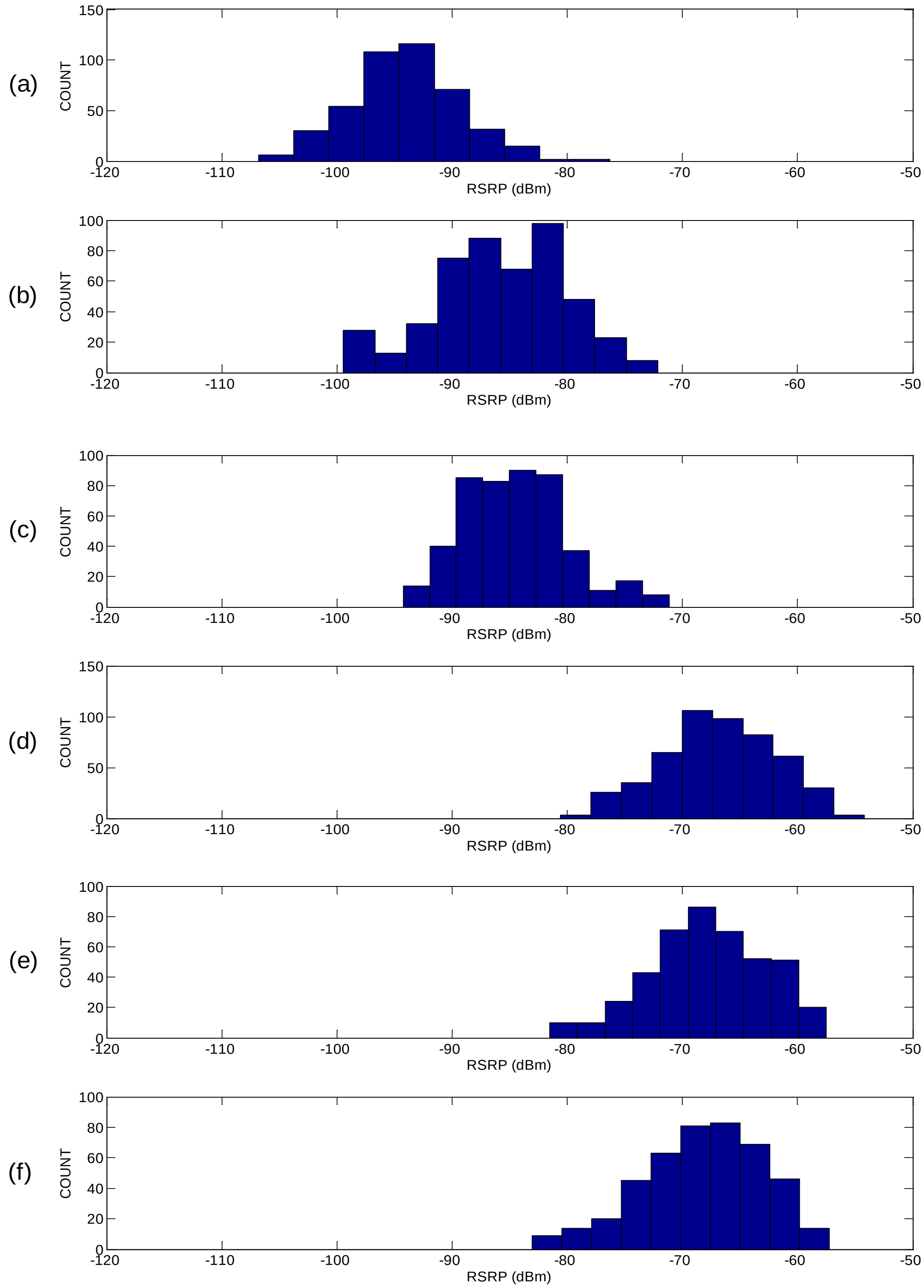

Figure 188. CEC stadium histograms of reference signal received power for different coverage combinations with a UDP downlink data flow. (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN.

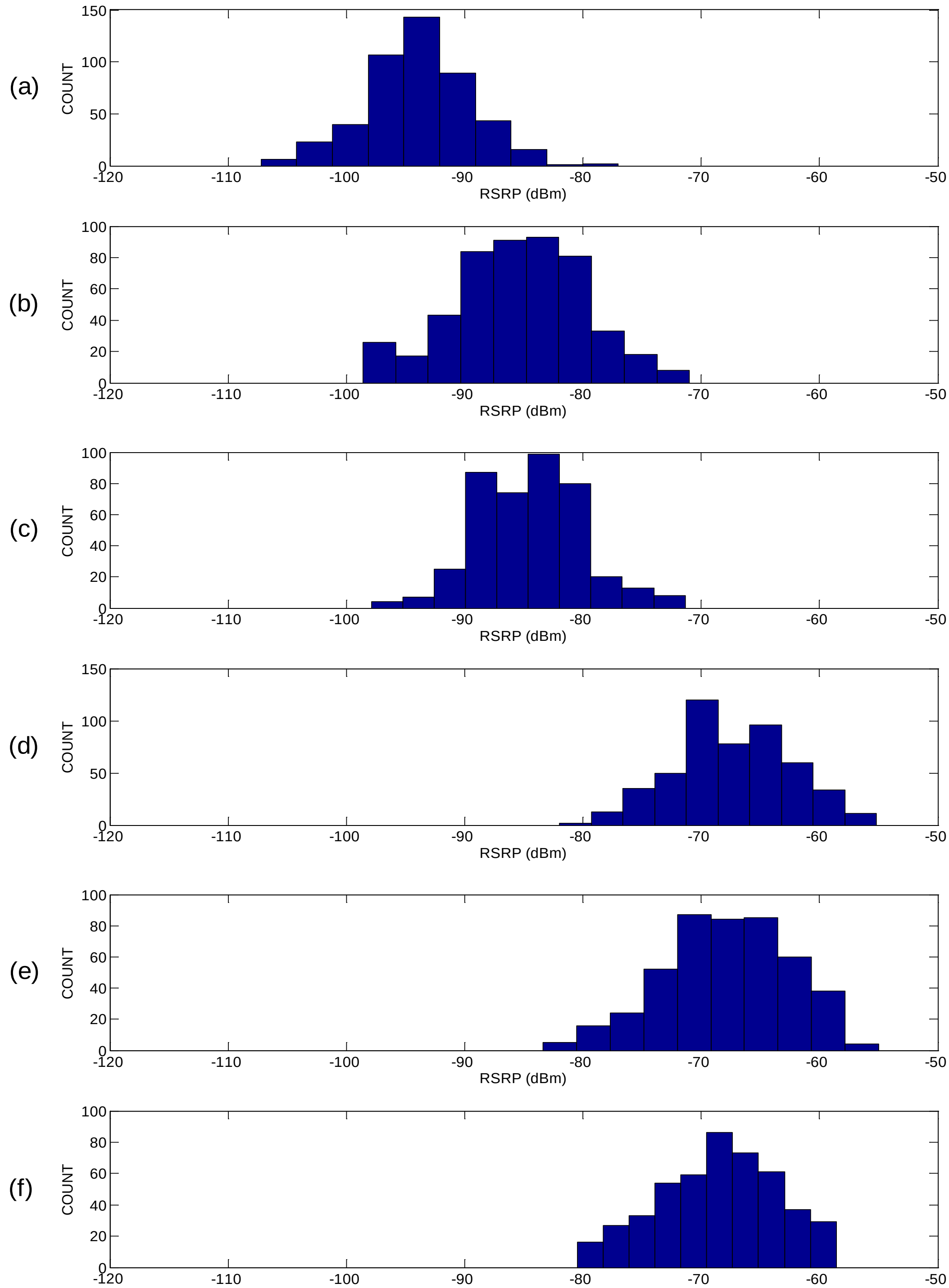

Figure 189. CEC stadium histograms of reference signal received power for different coverage combinations with a UDP uplink data flow. (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN.

Table 97. CEC stadium RSRP statistics for a UDP downlink data flow.

Coverage Combination	Mean RSRP (dBm)	Median RSRP (dBm)	Standard Deviation (dBm)	Min RSRP (dBm)	Max RSRP (dBm)
PSCR MN	-93.9	-94.0	4.7	-106.8	-76.3
COW 40 W	-85.8	-85.7	5.6	-99.4	-72.1
PSCR MN + COW 40 W	-84.5	-84.7	4.4	-94.3	-71.1
SCDA 1 W	-66.9	-66.7	4.9	-80.6	-54.2
SCDA 1 W + COW 40 W	-67.9	-68.0	5.0	-81.5	-57.5
SCDA 1 W + COW 40 W + PSCR MN	-68.3	-67.8	5.2	-83.1	-57.3

Table 98. CEC stadium RSRP statistics for a UDP uplink data flow.

Coverage Combination	Mean RSRP (dBm)	Median RSRP (dBm)	Standard Deviation (dBm)	Min RSRP (dBm)	Max RSRP (dBm)
PSCR MN	-93.4	-93.8	4.4	-107.2	-77.0
COW 40 W	-85.4	-85.1	5.6	-98.6	-71.0
PSCR MN + COW 40 W	-54.5	-84.5	4.5	-97.9	-71.4
SCDA 1 W	-67.3	-67.5	4.9	-82.0	-55.2
SCDA 1 W + COW 40 W	-67.8	-67.7	5.3	-83.4	-55.0
SCDA 1 W + COW 40 W + PSCR MN	-68.6	-68.3	5.1	-80.5	-58.6

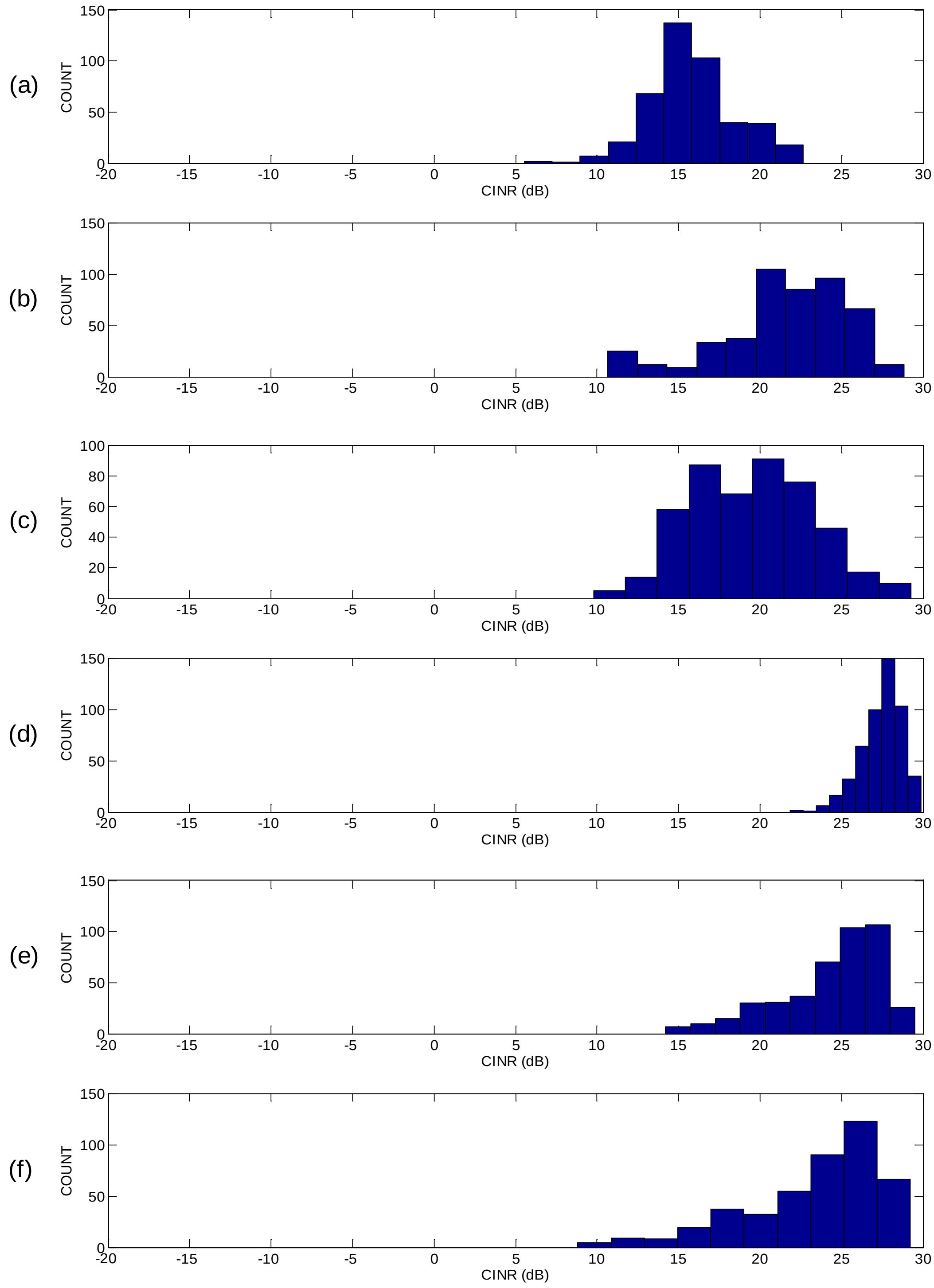

Figure 190. CEC stadium histograms of CINR for different coverage combinations with a UDP downlink data flow, (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN.

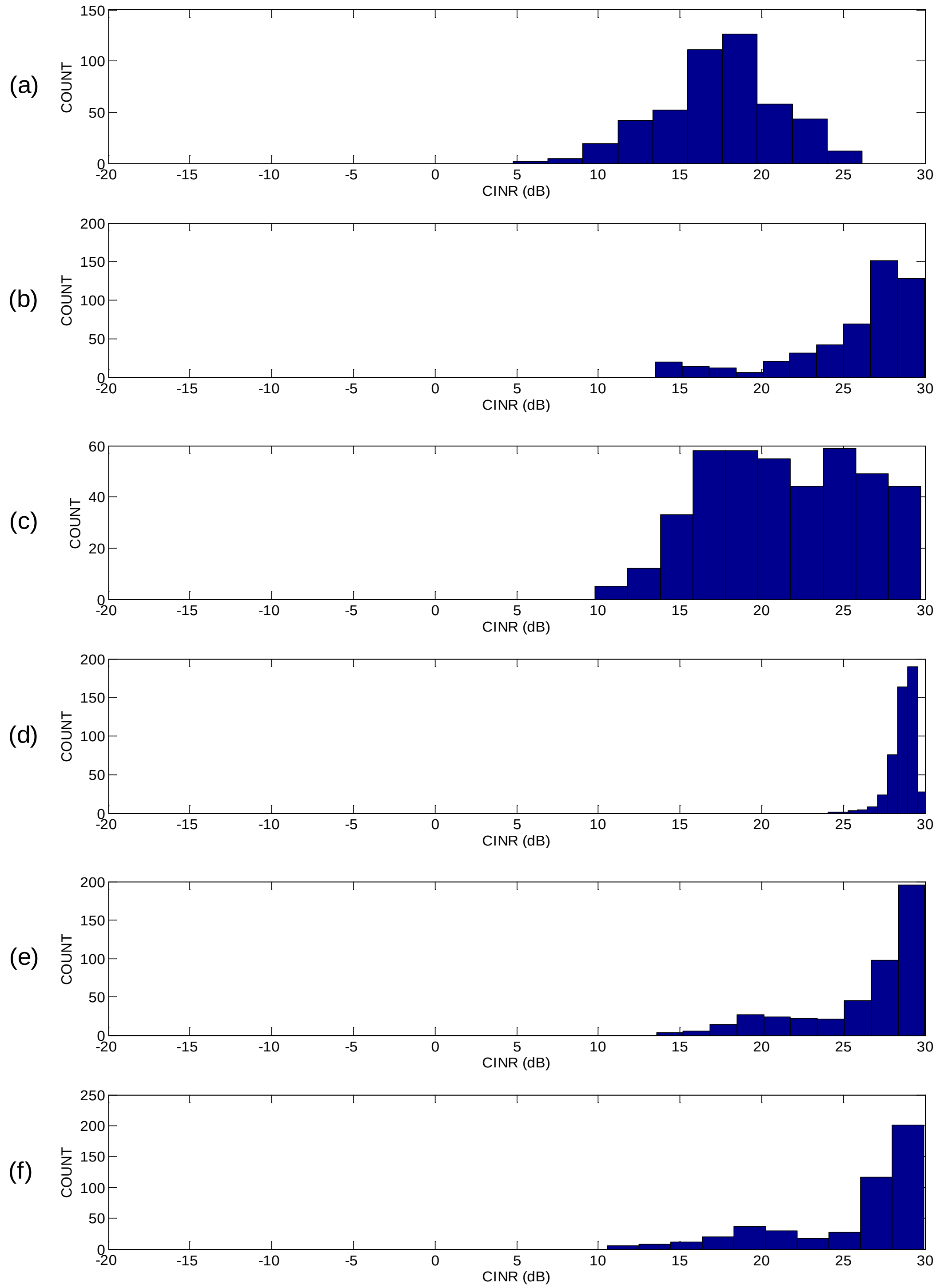

Figure 191. CEC stadium histograms of CINR for different coverage combinations with a UDP uplink data flow, (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN.

Table 99. CEC stadium CINR statistics for a UDP downlink data flow.

Coverage Combination	Mean CINR (dB)	Median CINR (dB)	Standard Deviation (dB)	Min CINR (dB)	Max CINR (dB)
PSCR MN	15.8	15.7	2.6	5.5	22.7
COW 40 W	21.5	22.0	3.9	10.7	28.8
PSCR MN + COW 40 W	19.5	19.7	3.7	9.8	29.3
SCDA 1 W	27.5	27.7	1.3	21.9	29.9
SCDA 1 W + COW 40 W	24.4	25.3	3.2	14.2	29.5
SCDA 1 W + COW 40 W + PSCR MN	23.3	24.7	4.2	8.8	29.2

Table 100. CEC stadium CINR statistics for a UDP uplink data flow.

Coverage Combination	Mean CINR (dB)	Median CINR (dB)	Standard Deviation (dB)	Min CINR (dB)	Max CINR (dB)
PSCR MN	17.4	17.7	3.6	4.8	26.2
COW 40 W	25.6	27.2	4.0	13.5	30.0
PSCR MN + COW 40 W	21.4	21.3	4.7	9.8	29.8
SCDA 1 W	28.7	28.9	0.7	24.1	30.1
SCDA 1 W + COW 40 W	26.3	28.1	3.6	13.6	30.0
SCDA 1 W + COW 40 W + PSCR MN	25.5	27.6	4.5	10.5	29.9

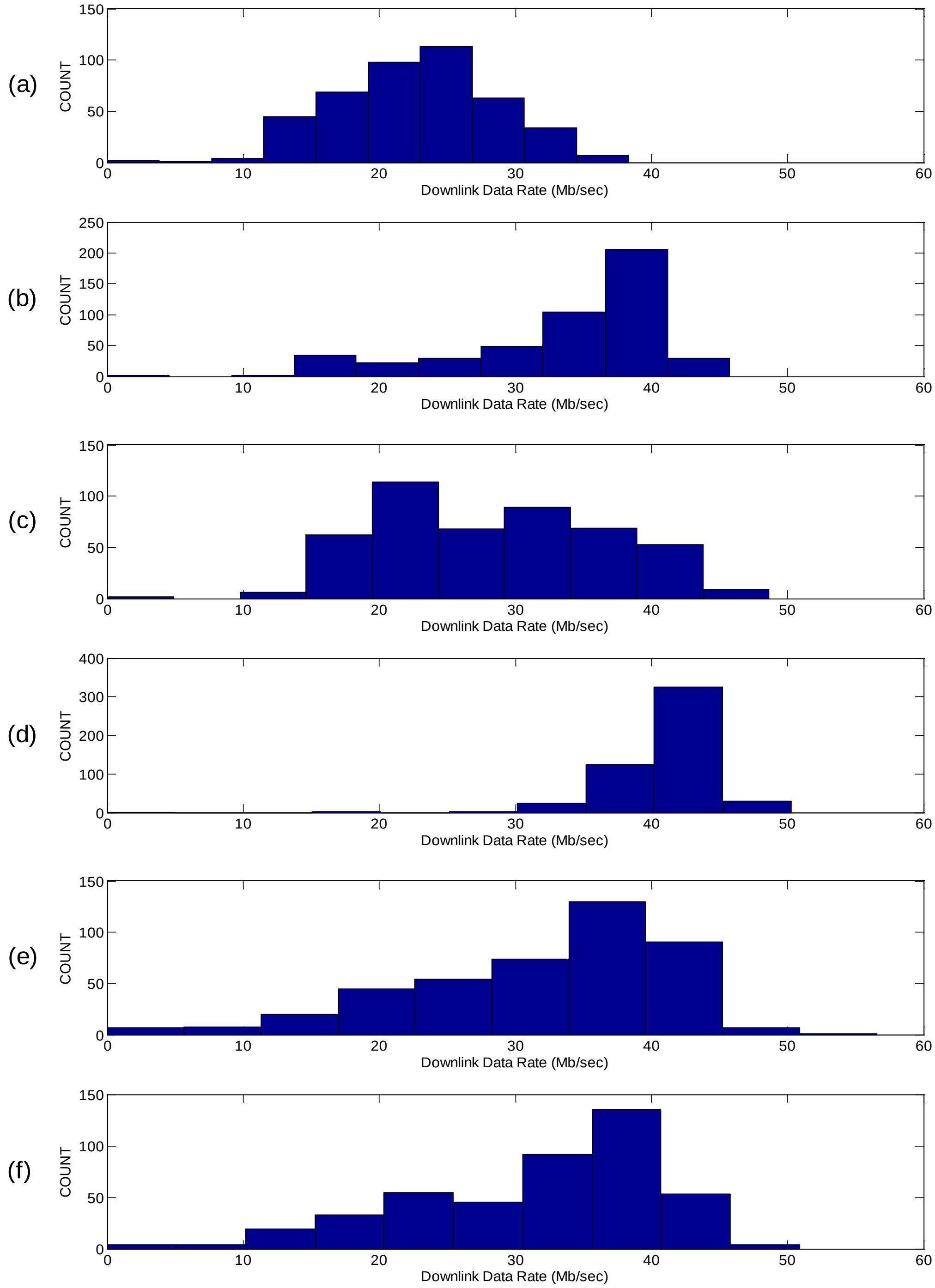

Figure 192. CEC stadium histograms of PDSCH downlink data rates for different coverage combinations with a UDP downlink data flow, (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN.

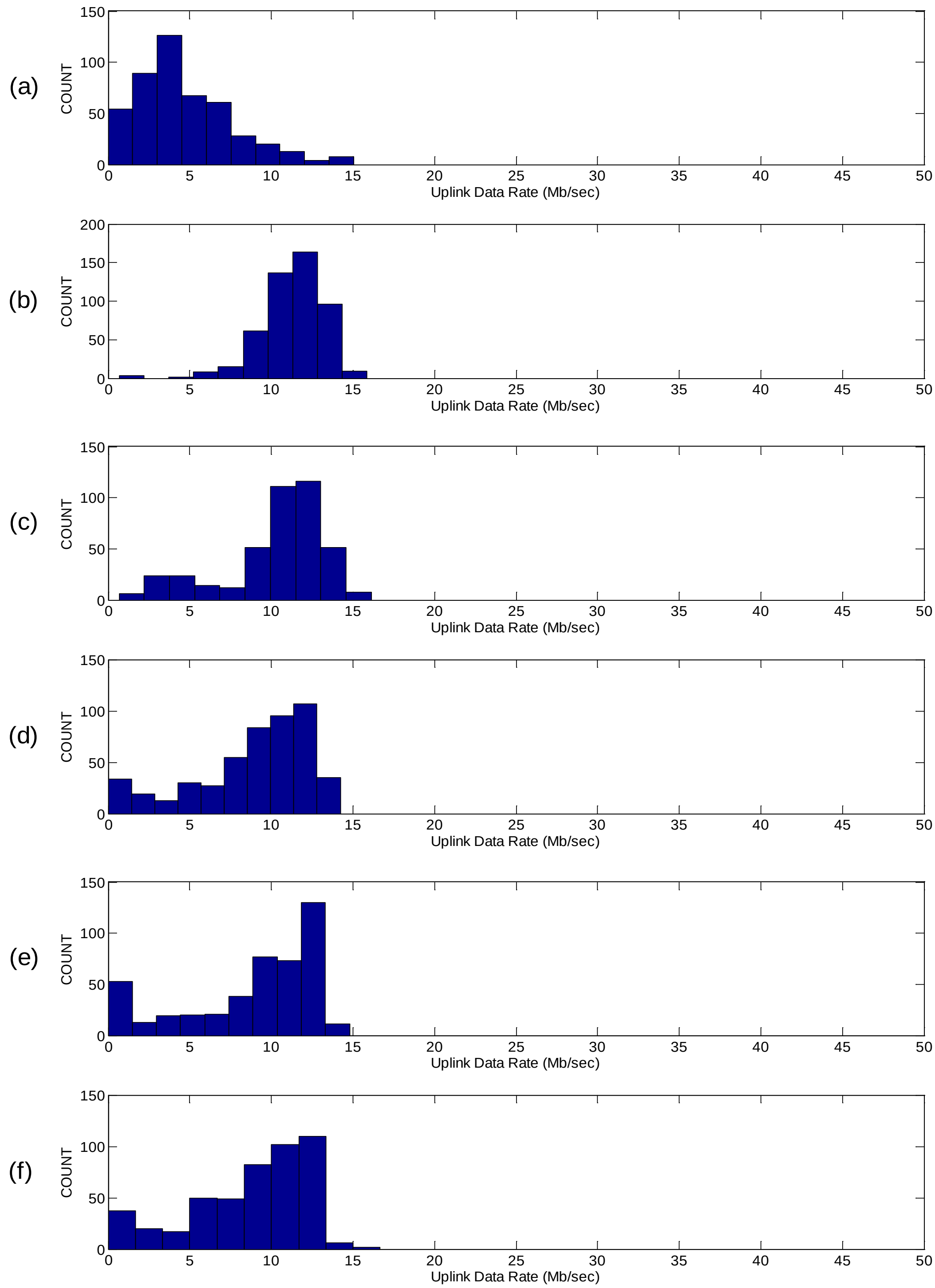

Figure 193. CEC stadium histograms of PUSCH uplink data rates for different coverage combinations with a UDP uplink data flow, (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN.

Table 101. CEC stadium PDSCH statistics for a UDP downlink data flow.

Coverage Combination	**Mean PDSCH (Mb/s)**	**Median PDSCH (Mb/s)**	**Standard Deviation (Mb/s)**	**Min PDSCH (Mb/s)**	**Max PDSCH (Mb/s)**
PSCR MN	22.7	23.0	5.9	0.008	38.3
COW 40 W	34.1	36.4	8.2	0.007	45.8
PSCR MN + COW 40 W	28.3	28.6	8.2	0.04	48.6
SCDA 1 W	40.2	40.6	3.7	0.004	50.2
SCDA 1 W + COW 40 W	31.9	34.8	9.6	0.004	56.5
SCDA 1 W + COW 40 W + PSCR MN	31.8	34.3	9.2	0.0	50.8

Table 102. CEC stadium PUSCH statistics for a UDP downlink data flow.

Coverage Combination	**Mean PUSCH (Mb/s)**	**Median PUSCH (Mb/s)**	**Standard Deviation (Mb/s)**	**Min PUSCH (Mb/s)**	**Max PUSCH (Mb/s)**
PSCR MN	4.71	4.1	3.0	0	15.1
COW 40 W	11.3	11.6	1.9	0.7	15.9
PSCR MN + COW 40 W	10.3	11.1	3.2	0.7	16.1
SCDA 1 W	8.8	9.8	3.6	0.0	14.2
SCDA 1 W + COW 40 W	8.8	10.1	4.1	0.0	14.8
SCDA 1 W + COW 40 W + PSCR MN	8.7	9.6	3.6	0.0	16.7

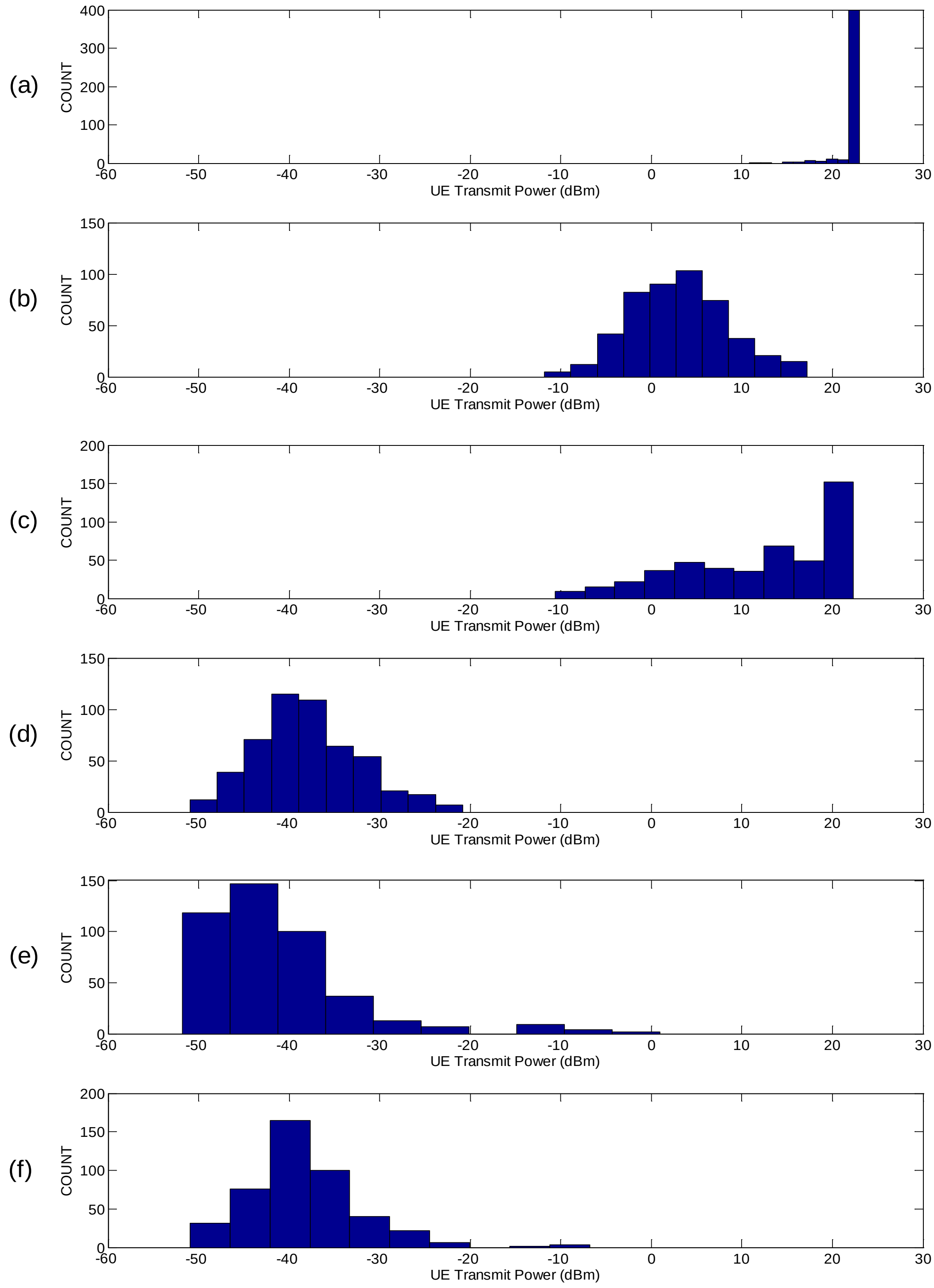

Figure 194. CEC stadium histograms of UE transmit power for different coverage combinations with a UDP downlink data flow. (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN.

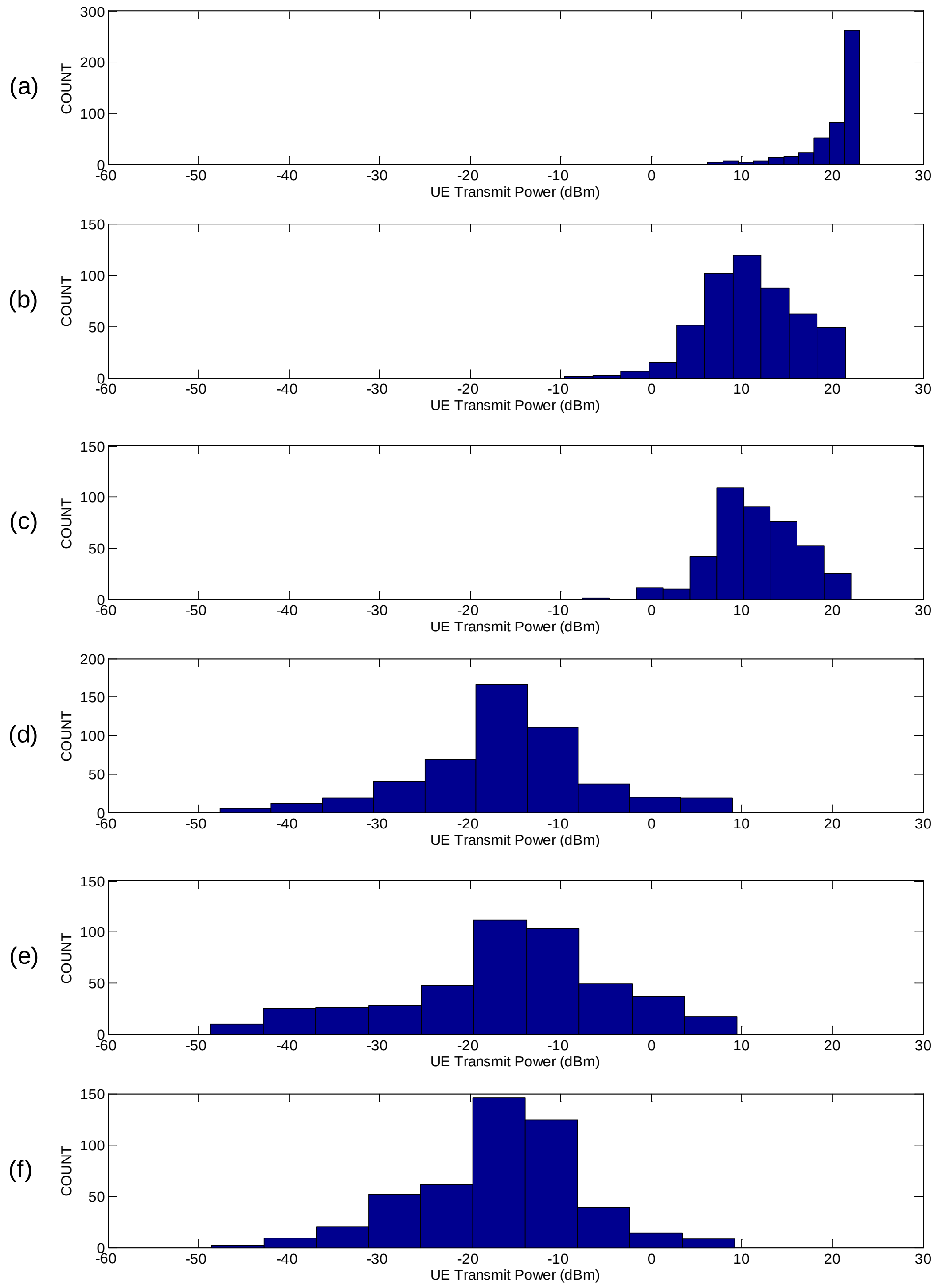

Figure 195. CEC stadium histograms of UE transmit power for different combinations with a UDP uplink data flow. (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN.

Table 103. CEC stadium UE transmit power statistics for a UDP downlink data flow.

Coverage Combination	Mean UEpwr (dBm)	Median UEpwr (dBm)	Standard Deviation (dBm)	Min UEpwr (dBm)	Max UEpwr (dBm)
PSCR MN	22.0	22.0	1.3	10.8	23.0
COW 40 W	3.0	3.1	5.4	-11.8	17.2
PSCR MN + COW 40 W	12.3	14.3	8.9	-10.6	22.3
SCDA 1 W	-37.9	-38.5	5.7	-51	-20.8
SCDA 1 W + COW 40 W	-41.3	-43.0	8.6	-51.8	1.0
SCDA 1 W + COW 40 W + PSCR MN	-38.4	-39.1	6.2	-51.0	-6.8

Table 104. CEC stadium UE transmit power statistics for a UDP uplink data flow.

Coverage Combination	Mean UEpwr (dBm)	Median UEpwr (dBm)	Standard Deviation (dBm)	Min UEpwr (dBm)	Max UEpwr (dBm)
PSCR MN	20.2	21.6	3.0	6.3	23.0
COW 40 W	11.0	10.7	5.2	-9.6	21.4
PSCR MN + COW 40 W	11.6	11.1	4.8	-7.6	22.1
SCDA 1 W	-16.1	-16.0	9.6	-47.7	8.9
SCDA 1 W + COW 40 W	-16.1	-15.1	11.9	-48.7	9.5
SCDA 1 W + COW 40 W + PSCR MN	-16.8	-16.0	8.9	-48.6	9.2

5.2 CEC Level 2 Measured Results

Level 2 of the CEC is located in the infrastructure section of the CEC, and it is one level below the stadium concourse and at street level with respect to Regent Drive, which runs along the west side of the CEC.

We collected data over the walk path described in Section 4.1. We performed measurements for the following seven coverage combinations:

- PSCR MN only at 40 W
- COW only at 40 W
- COW at 40 W + PSCR MN
- SCDA only at 1 W
- SCDA at 1W + COW at 40 W
- SCDA at 1W + COW at 40 W + PSCR MN
- SCDA at 5 W + COW at 40 W + PSCR MN (Levels 1 and 2 only)

The first six coverage configurations are identical to the ones we used for the stadium tests. We added the last configuration to improve coverage deep in the interior of the FOS.

Figures 196–202 show the RSRP measurements superimposed on the CEC level-2 floor plan. The RSRP comparative histograms, as a function of coverage, are shown in Figures 203 and 204, and the summary statistics are given in Tables 105 and 106. Figure 196 shows that the PSCR MN has very low RSRP signal levels. In this case we see median and peak levels of −104 dBm and −89 dBm respectively. This is caused by the combination of the RF attenuation of interior walls and the blockage effects of the stadium section. Placing the COW on the north side of the CEC circumvents this problem by providing direct illumination of the infrastructure portion of the CEC from the north. As the results show, the signal level improvements are dramatic. We now see a 30 dB improvement in median signal levels over that of the macro network. The resulting RSRP data spreads are still large due to higher path losses deep inside the building.

Adding the macro network to the COW provides very little change in realized RSRP levels. The SCDA system does provide good coverage over sections of the walk path that are adjacent to the stadium, but its coverage rapidly diminishes on other portions of the walk path because of the RF attenuation of interior walls. Much improved coverage is obtained when the COW and the SCDA are part of the coverage package. We see median and peak levels of −69 dBm and −50 dBm, respectively. The COW has the most impact on the northern part of the walk route, while the small cell provides coverage on the southern part—the COW and SCDA complement each other. The best results occur when the SCDA power level is increased to 5 W.

The CINR results are shown in Figures 205 and 206 and Tables 107 and 108. With one exception, the observed trends closely parallel those of the RSRP results. The exception occurs when the SCDA at 5 W is used in conjunction with the COW and the macro network. The CINR values show an increased spread with an increased count of low values. This is due to increased neighbor cell interference levels produced by the higher power of the SCDA system.

The PDSCH downlink data rates are shown in Figure 207. The summary statistics are shown in Table 109. The PSCR MN provides wide spread of PDSCH values ranging from 0 kb/s to above 25 Mb/s. The resulting median and peak data rates are 11 Mb/s and 26 Mb/s. Low rates occur in the middle portion of the walk path, deep inside the building, where the coverage is poor. The COW improves the situation considerably. The data rates now vary from 16 Mb/s to values in excess of 45 Mb/s. A similar distribution occurs when the macro network is added to the coverage. A wide spread of data occurs when coverage is provided by the SCDA. High data rates are realized on portions of the walk path that are adjacent to the stadium, but the rates decrease rapidly on other portions. The COW by itself produces better overall data rates than when it used in tandem with the SCDA and the macro network. Handovers occur when multiple coverage elements are used and these produce reduced data rates—careful network optimization is needed to improve the data rates and correct this situation.

The PUSCH uplink data rates are shown in Figure 208, with summary statistics in Table 110. The PSCR MN produces a preponderance of low data rates, due to the high path losses and lower UE transmit power levels. The resulting median and peak data rates are 0.3 Mb/s and 6 Mb/s respectively. The COW greatly improves the results and data rates vary over the range of 5 Mb/s to 16 Mb/s, with median and peak data rates of 12 Mb/s and 16 Mb/s respectively. The SCDA again produces good data rates over the walk path segments that are adjacent to the stadium, but these rapidly diminish on other segments. We see the same reduction in data rates, due to handovers, when the SCDA is combined with other coverage elements—the COW and the macro network.

The UE transmit power level results are shown in Figures 209 and 210 for UDP downlink and uplink data flows respectively. Summary statistics are given in Tables 111 and 112. The UE power is maximized when the PSCR MN is used for coverage. For a downlink data flow we see median and peak levels of 22 dBm and 23 dBm respectively. In the case of an uplink data flow, we see a median UE transmit power level of 19 dBm and a peak level of 23 dBm. This is a result of the high path losses between the UE and the serving eNB on Green Mountain. The pattern of results is somewhat different here in that the best overall performance is obtained using the combination of the SCDA at 1 W, COW, and PSCR MN, where we see a median UE transmit power level of -22 dBm and a peak level of 4 dBm.

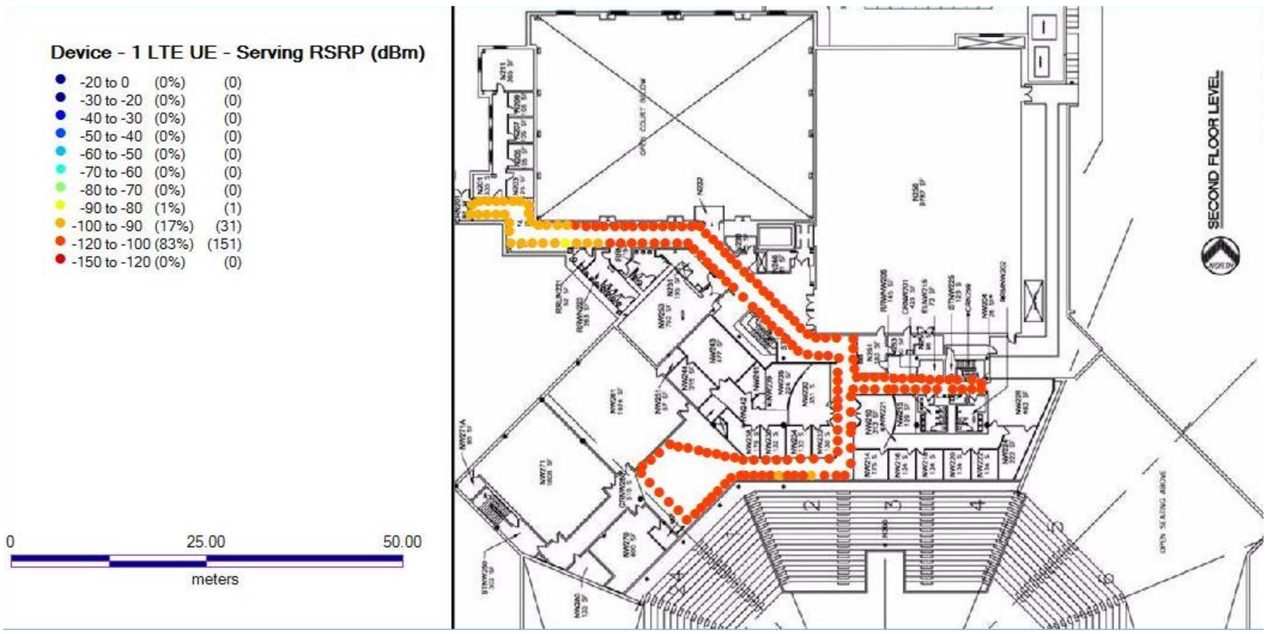

Figure 196. CEC level 2 reference signal received power (RSRP) for a UDP downlink data flow with the PSCR MN at 40 W. North is at the top of the figure.

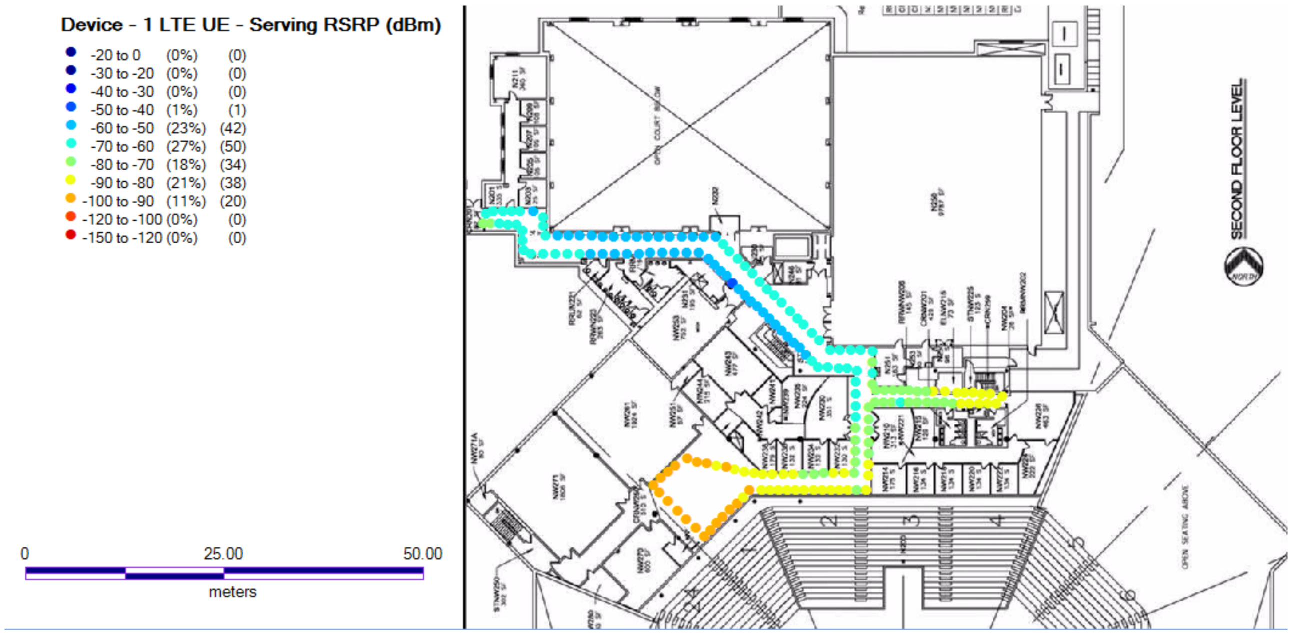

Figure 197. CEC level 2 reference signal received power (RSRP) for a UDP downlink data flow with the COW at 40 W. North is at the top of the figure.

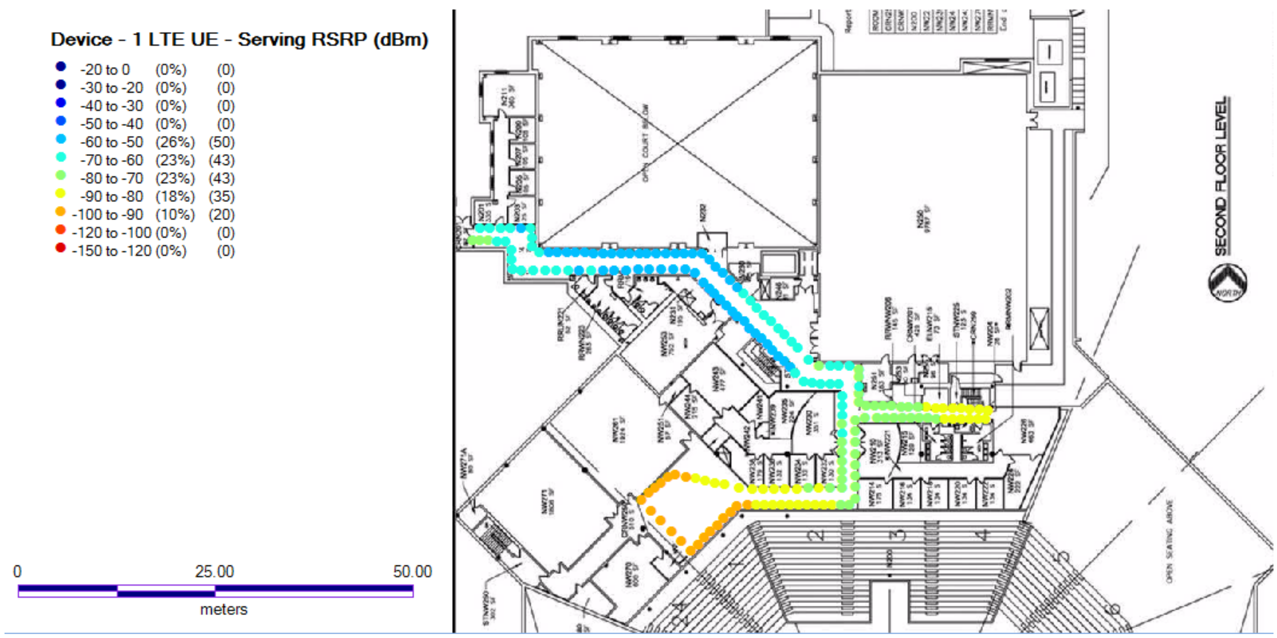

Figure 198. CEC level 2 reference signal received power (RSRP) for a UDP downlink data flow with the COW at 40 W and the PSCR MN. North is at the top of the figure.

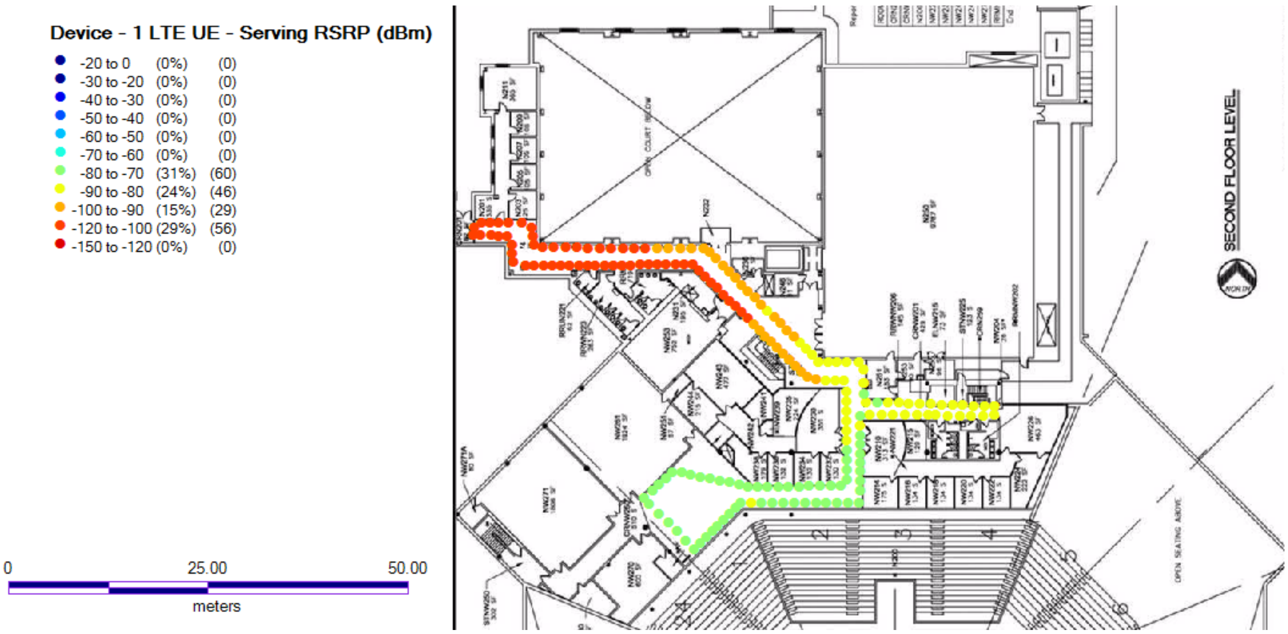

Figure 199. CEC level 2 reference signal received power for a UDP downlink data flow with the SCDA at a transmit power of 1 W. North is at the top of the figure.

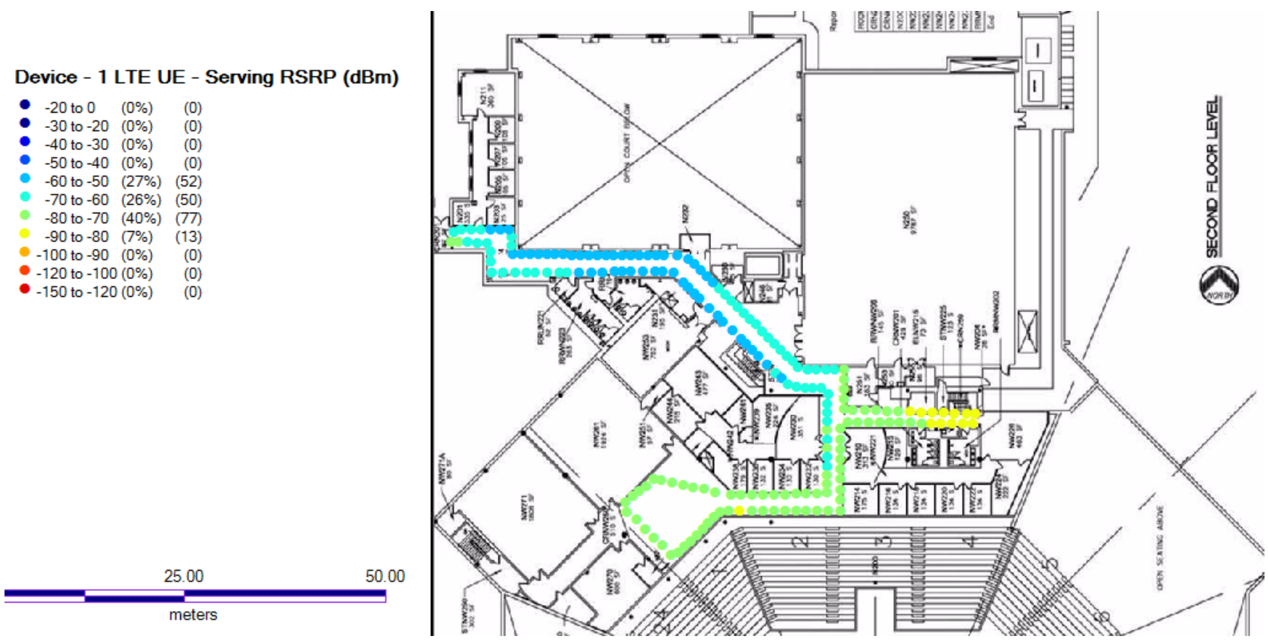

Figure 200. CEC level 2 reference signal received power (RSRP) for a UDP downlink data flow with the SCDA at a transmit power of 1 W and a COW at 40 W. North is at the top of the figure.

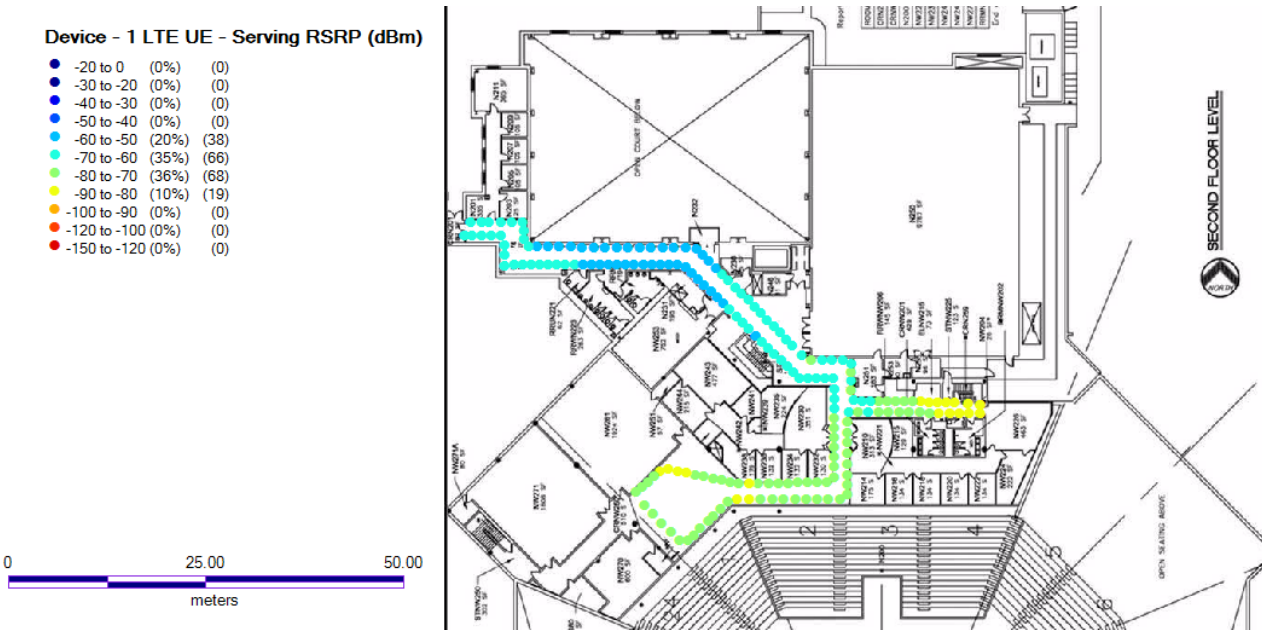

Figure 201. CEC level 2 reference signal received power (RSRP) for a UDP downlink data flow with the SCDA at a transmit power of 1 W and a COW at 40 W and the PSCR MN. North is at the top of the figure.

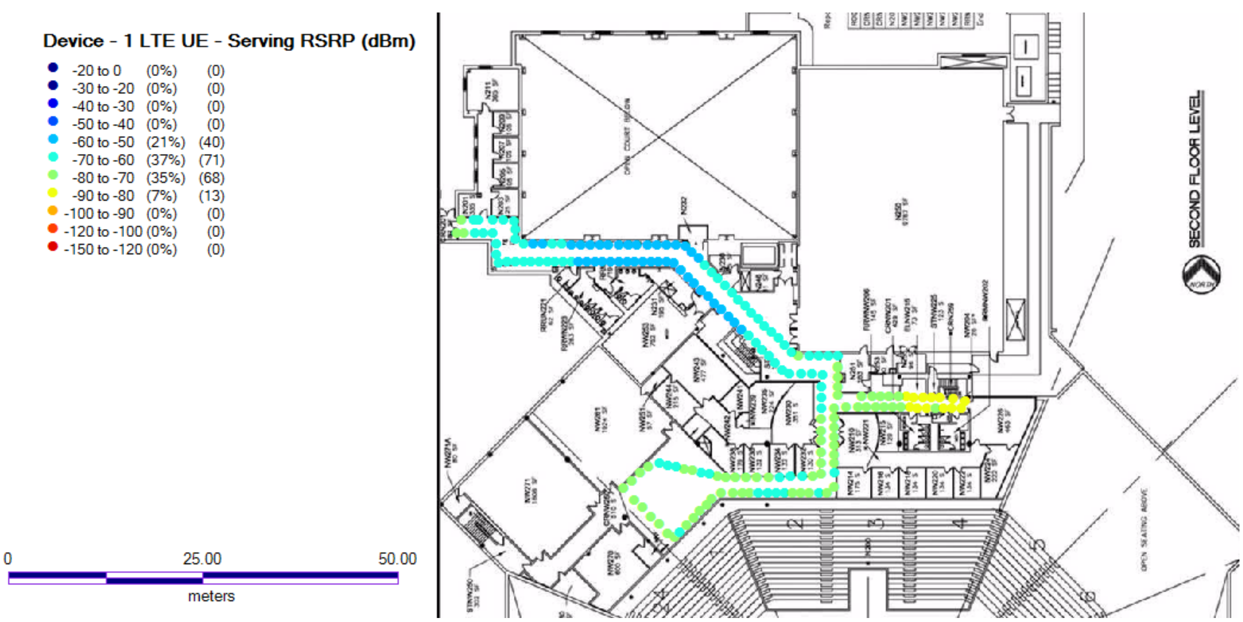

Figure 202. CEC level 2 reference signal received power (RSRP) for a UDP downlink data flow with the small cell and discrete antennas at the maximum transmit power of 5 W and a COW at 40 W. North is at the top of the figure.

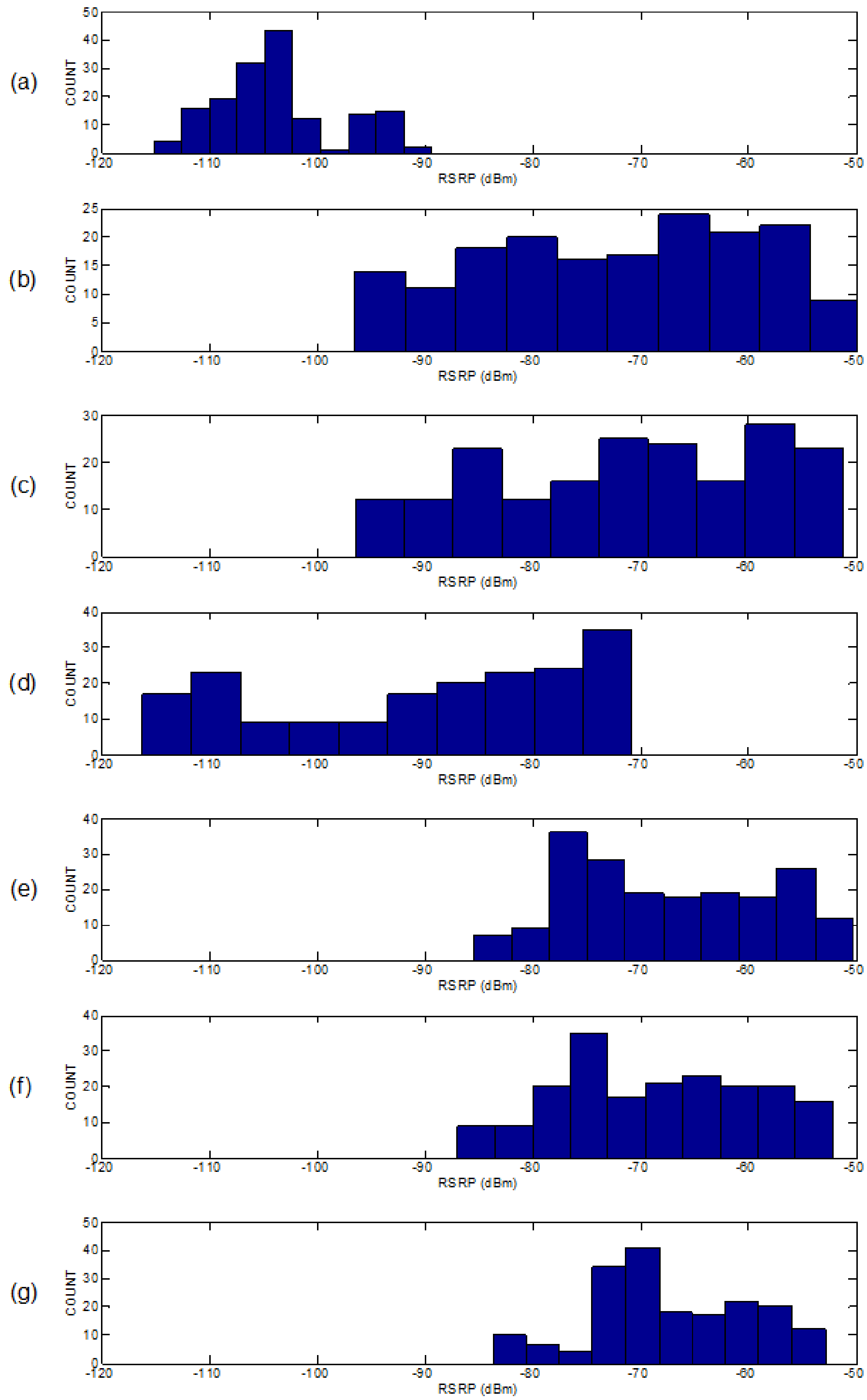

Figure 203. CEC level 2 histograms of reference signal received power for different coverage combinations with UDP downlink data flow. (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN, (g) SCDA at a maximum power level of 5 W and COW at 40 W.

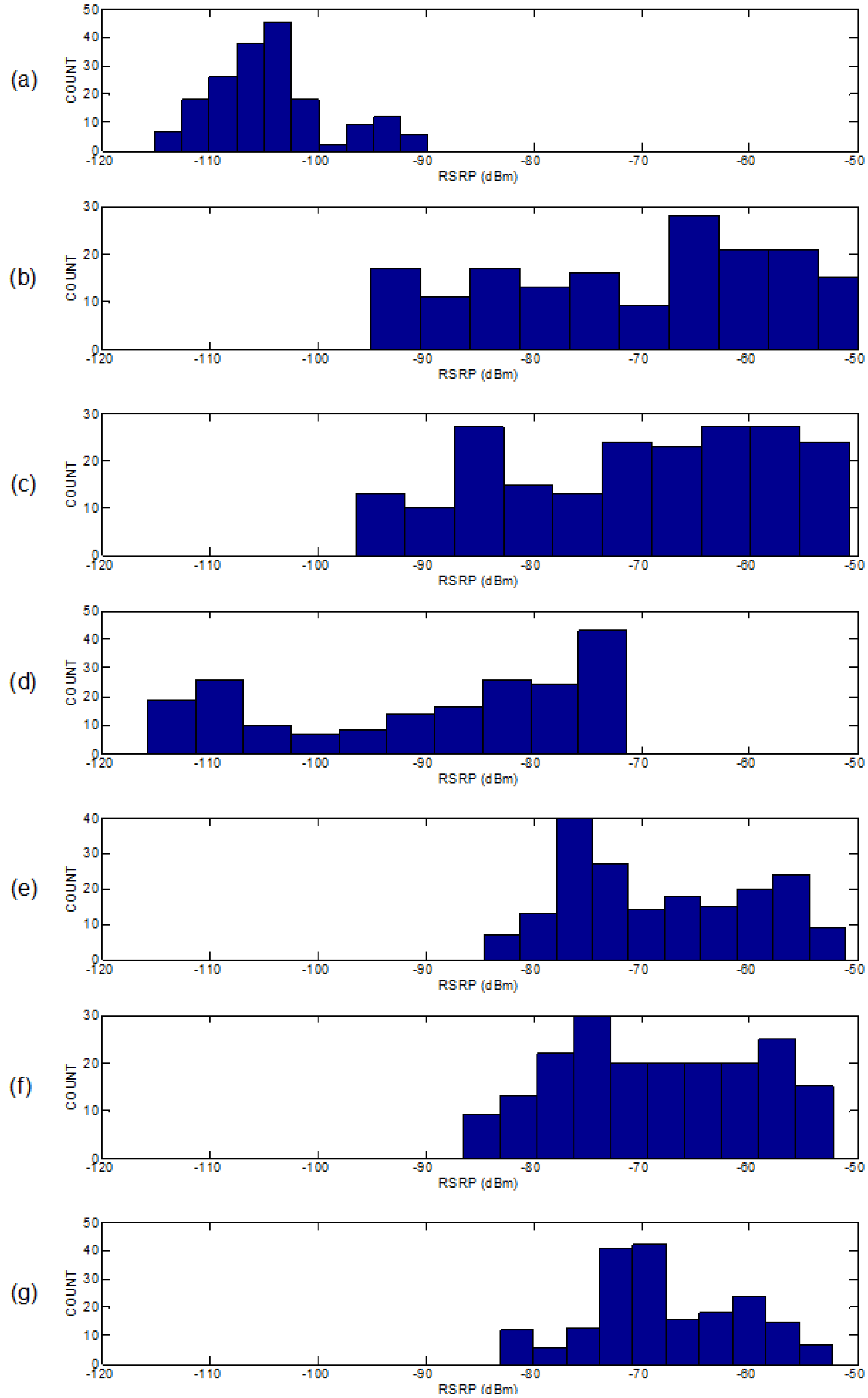

Figure 204. CEC level 2 histograms of reference signal received power for different coverage combinations with UDP uplink data flow. (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN, (g) SCDA at a maximum power level of 5 W and COW at 40 W.

Table 105. CEC level 2 RSRP statistics for a UDP downlink data flow.

Coverage Combination	Mean RSRP (dBm)	Median RSRP (dBm)	Standard Deviation (dBm)	Min RSRP (dBm)	Max RSRP (dBm)
PSCR MN	-103.6	-103.7	5.6	-115.2	-89.4
COW 40 W	-72.3	-70.8	12.6	-96.5	-49.6
PSCR MN + COW 40 W	-71.3	-86.5	12.6	-96.5	-51.2
SCDA 1 W	-90.1	-86.5	14.0	-116.3	-70.8
SCDA 1 W + COW 40 W	-67.6	-69.0	9.1	-85.5	-50.3
SCDA 1 W + COW 40 W + PSCR MN	-68.7	-68.5	8.8	-87.0	-52.2
SCDA 5 W + COW 40 W + PSCR MN	-67.3	-68.5	7.4	-83.7	-52.9

Table 106. CEC level 2 RSRP statistics for a UDP uplink data flow.

Coverage Combination	Mean RSRP (dBm)	Median RSRP (dBm)	Standard Deviation (dBm)	Min RSRP (dBm)	Max RSRP (dBm)
PSCR MN	-104.3	-104.9	5.6	-115.2	-89.8
COW 40 W	-70.6	-67.3	13.1	-95.1	-49.0
PSCR MN + COW 40 W	-70.7	-69.2	12.7	-96.5	-50.8
SCDA 1 W	-90.0	-85.3	14.3	-115.8	-71.4
SCDA 1 W + COW 40 W	-68.2	-69.5	8.8	-84.6	-51.1
SCDA 1 W + COW 40 W + PSCR MN	-68.5	-68.4	9.0	-86.6	-52.2
SCDA 5 W + COW 40 W + PSCR MN	-67.8	-69.3	7.1	-83.1	-52.3

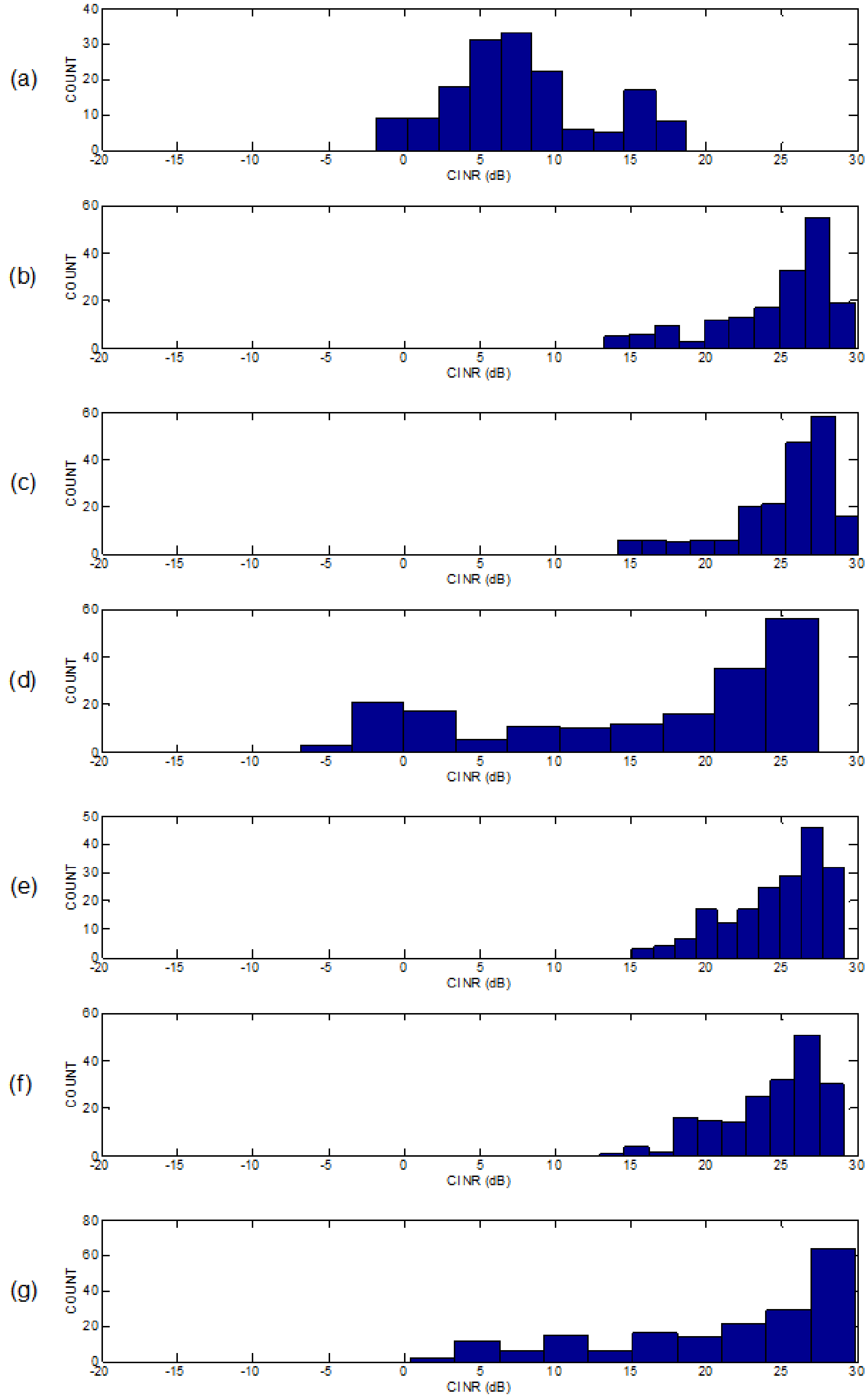

Figure 205. CEC level 2 histograms of CINR for different coverage combinations with a UDP downlink data flow. (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN, (g) SCDA at a maximum power level of 5 W and COW at 40 W.

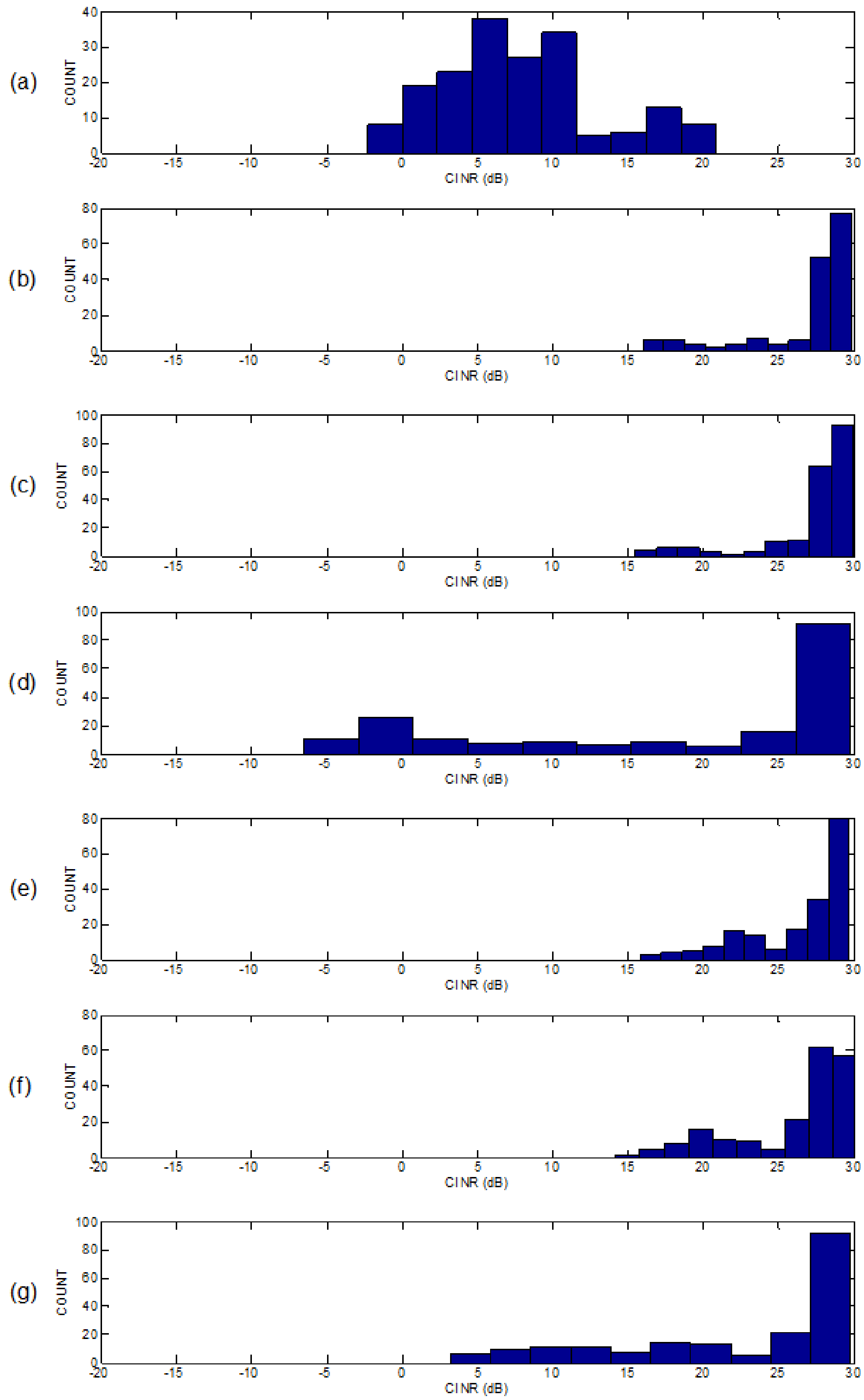

Figure 206. CEC level 2 histograms of CINR for different coverage combinations with a UDP uplink data flow. (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN, (g) SCDA at a maximum power level of 5 W and COW at 40 W.

Table 107. CEC level 2 CINR statistics for a UDP downlink data flow.

Coverage Combination	Mean CINR (dB)	Median CINR (dB)	Standard Deviation (dB)	Min CINR (dB)	Max CINR (dB)
PSCR MN	7.8	7.4	4.9	-1.8	18.7
COW 40 W	24.6	26.2	3.9	13.3	29.8
PSCR MN + COW 40 W	25.1	26.3	3.5	14.1	30.1
SCDA 1 W	15.8	20.1	10.2	-6.9	27.4
SCDA 1 W + COW 40 W	24.6	25.5	3.2	15.1	29.1
SCDA 1 W + COW 40 W + PSCR MN	24.3	25.4	3.5	13.0	29.1
SCDA 5 W + COW 40 W + PSCR MN	21.2	24.1	7.8	0.4	29.9

Table 108. CEC level 2 CINR statistics for a UDP uplink data flow.

Coverage Combination	Mean CINR (dB)	Median CINR (dB)	Standard Deviation (dB)	Min CINR (dB)	Max CINR (dB)
PSCR MN	7.9	7.2	5.3	-2.3	20.8
COW 40 W	26.9	28.4	3.4	16.0	29.9
PSCR MN + COW 40 W	27.2	28.4	3.2	15.4	30.0
SCDA 1 W	17.6	25.6	12.6	-6.6	29.8
SCDA 1 W + COW 40 W	26.3	27.7	3.4	15.8	29.7
SCDA 1 W + COW 40 W + PSCR MN	26.1	28.1	3.8	14.2	30.3
SCDA 5 W + COW 40 W + PSCR MN	22.3	26.6	8.0	3.2	29.8

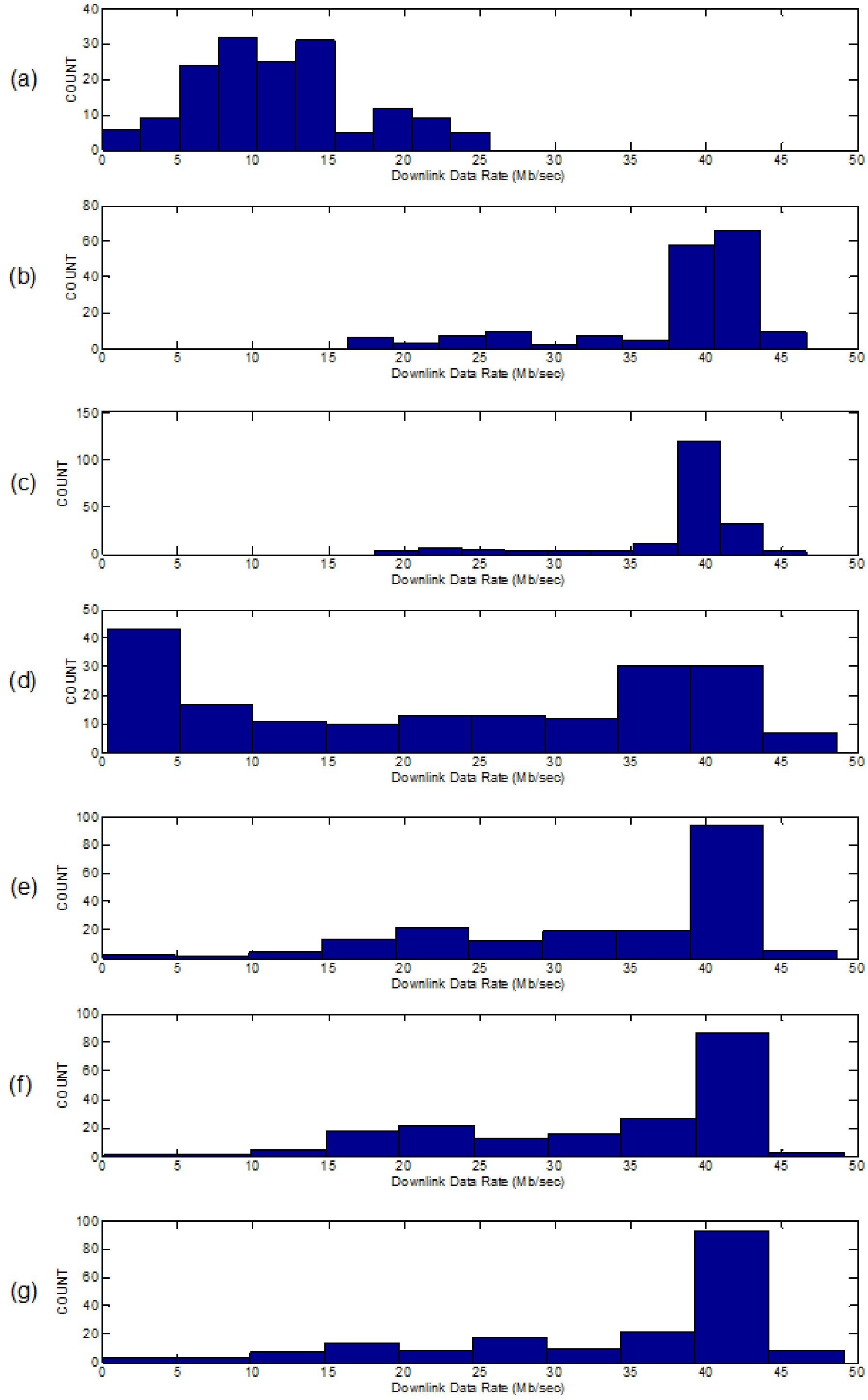

Figure 207. CEC level 2 histograms of PDSCH downlink data rates for different coverage combinations with a UDP uplink data flow. (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN, (g) SCDA at a maximum power level of 5 W and COW at 40 W.

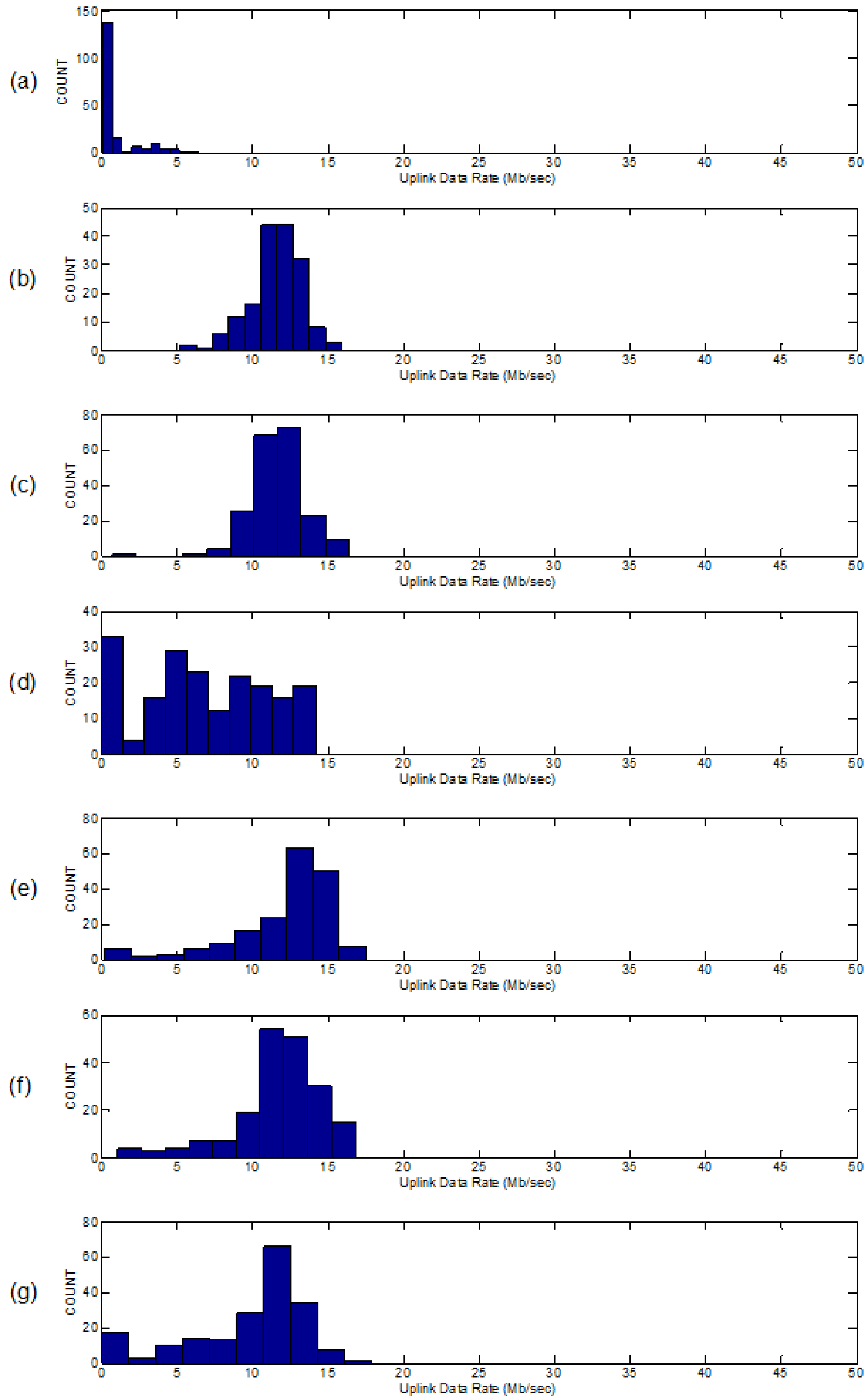

Figure 208. CEC level 2 histograms of PUSCH uplink data rates for different coverage combinations with a UDP uplink data flow. (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN, (g) SCDA at a maximum power level of 5 W and COW at 40 W.

Table 109. CEC level 2 PDSCH statistics for a UDP downlink data flow.

Coverage Combination	Mean PDSCH (Mb/s)	Median PDSCH (Mb/s)	Standard Deviation (Mb/s)	Min PDSCH (Mb/s)	Max PDSCH (Mb/s)
PSCR MN	11.7	11.2	5.6	0.0	25.7
COW 40 W	37.8	40.5	6.6	16.3	46.6
PSCR MN + COW 40 W	38.6	40.6	5.4	18.1	46.6
SCDA 1 W	22.8	23.9	15.3	0.4	48.6
SCDA 1 W + COW 40 W	33.6	39.6	9.5	0.1	48.7
SCDA 1 W + COW 40 W + PSCR MN	33.3	38.1	9.5	0.1	49.1
SCDA 5 W + COW 40 W + PSCR MN	11.6	40.0	10.5	0.2	49.1

Table 110. CEC level 2 PUSCH statistics for a UDP uplink data flow.

Coverage Combination	Mean PUSCH (Mb/s)	Median PUSCH (Mb/s)	Standard Deviation (Mb/s)	Min PUSCH (Mb/s)	Max PUSCH (Mb/s)
PSCR MN	0.8	0.3	1.2	0.1	6.4
COW 40 W	11.6	11.7	1.76	5.2	15.9
PSCR MN + COW 40 W	11.7	11.7	1.8	0.7	16.4
SCDA 1 W	6.8	6.6	4.3	0.0	14.1
SCDA 1 W + COW 40 W	12.1	13.1	3.4	0.2	17.4
SCDA 1 W + COW 40 W + PSCR MN	11.6	12.0	3.0	1.1	16.8
SCDA 5 W + COW 40 W + PSCR MN	9.8	11.2	3.9	0.0	17.9

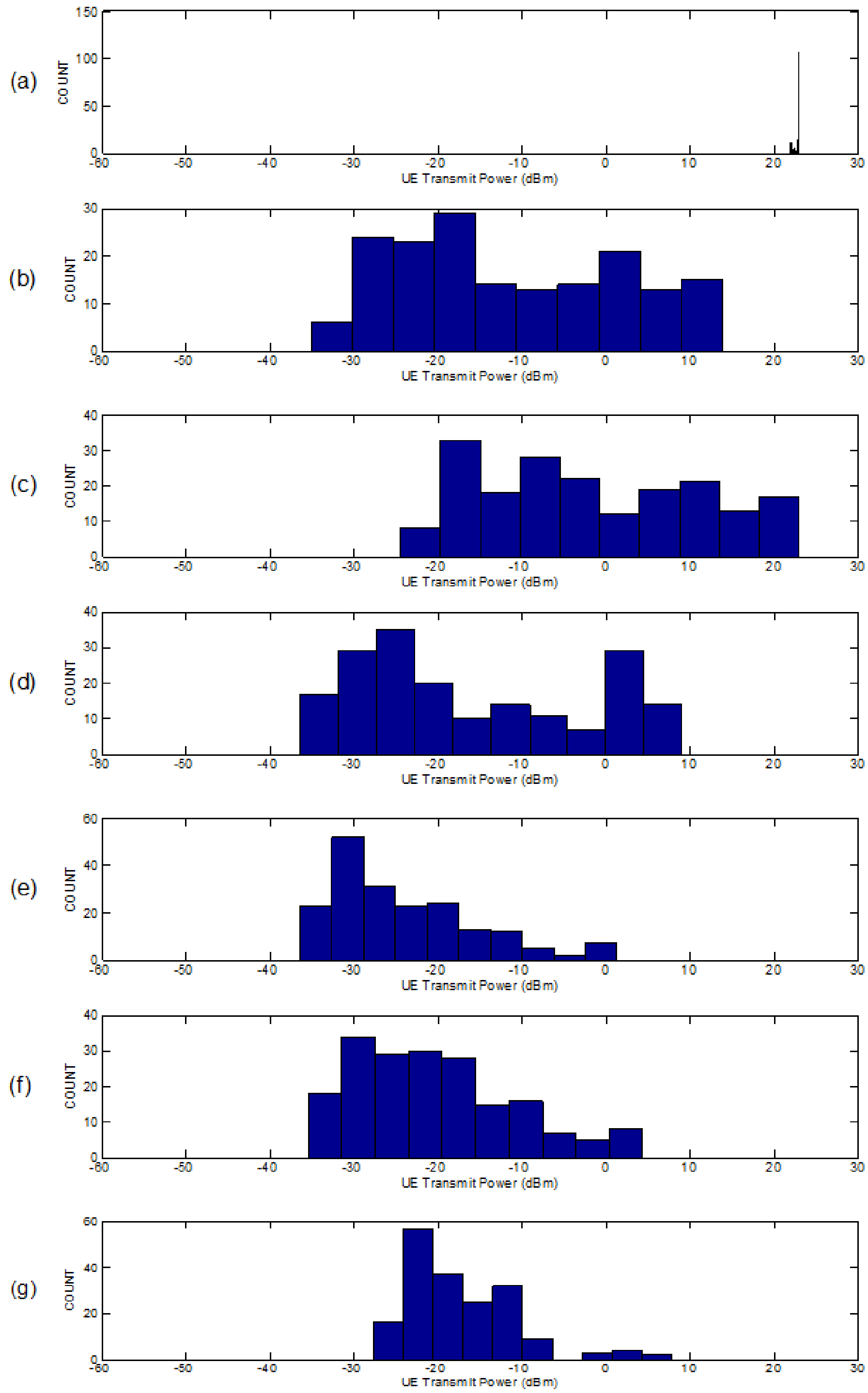

Figure 209. CEC level 2 histograms of UE transmit power for different coverage configurations with UDP downlink data flow. (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN, (g) SCDA at a maximum power level of 5 W and COW at 40 W.

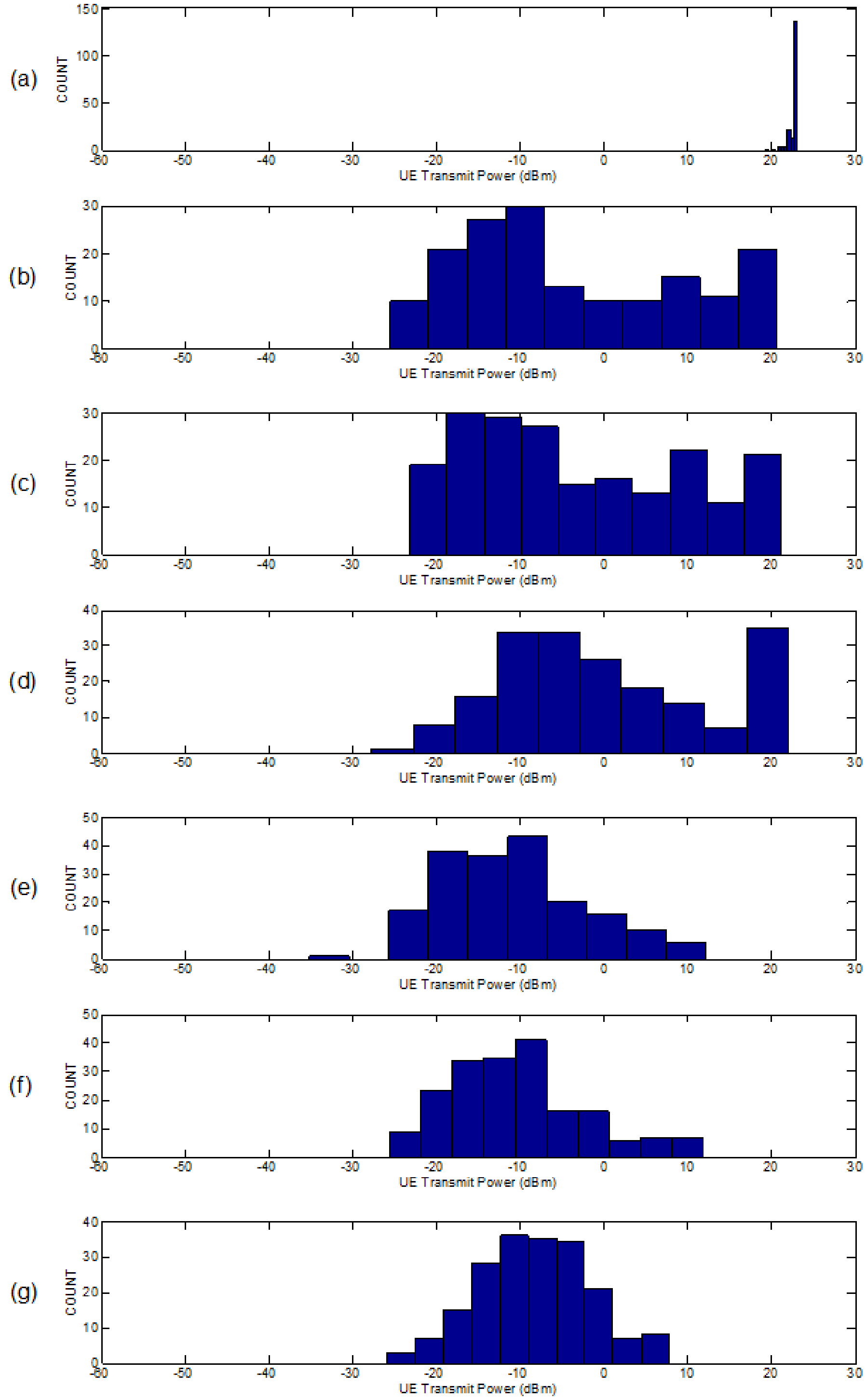

Figure 210. CEC level 2 histograms of UE transmit power for different coverage combinations with a UDP uplink data flow. (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN, (g) SCDA at a maximum power level of 5 W and COW at 40 W.

Table 111. CEC level 2 UE transmit power statistics for a UDP downlink data flow.

Coverage Combination	Mean UE tpwr (dBm)	Median UE tpwr (dBm)	Standard Deviation (dBm)	Min UE tpwr (dBm)	Max UE tpwr (dBm)
PSCR MN	22.8	23.0	0.3	22.0	23.0
COW 40 W	-11.4	-14.3	13.3	-35.2	13.9
PSCR MN + COW 40 W	-1.7	-3.7	13.1	-24.5	23.0
SCDA 1 W	-16.0	-20.5	13.6	-36.4	9.1
SCDA 1 W + COW 40 W	-24.0	-26.5	8.6	-36.4	1.3
SCDA 1 W + COW 40 W + PSCR MN	-20.4	-21.6	9.5	-35.5	4.4
SCDA 5 W + COW 40 W + PSCR MN	-8.3	-7.7	6.8	-25.9	7.8

Table 112. CEC level 2 UE transmit power statistics for a UDP uplink data flow.

Coverage Combination	Mean UE tpwr (dBm)	Median UE tpwr (dBm)	Standard Deviation (dBm)	Min UE tpwr (dBm)	Max UE tpwr (dBm)
PSCR MN	22.7	23.0	0.6	19.3	23.0
COW 40 W	-3.6	-7.7	13.3	-25.6	20.7
PSCR MN + COW 40 W	-3.0	-6.0	12.9	-23.2	21.1
SCDA 1 W	0.3	-2.7	12.6	-27.8	22.0
SCDA 1 W + COW 40 W	-10.6	-11.4	8.5	-35.2	12.2
SCDA 1 W + COW 40 W + PSCR MN	-10.3	-11.3	8.2	-25.7	11.8
SCDA 5 W + COW 40 W +PSCR MN	-8.3	-7.7	6.8	-25.9	7.8

5.3 CEC Level 1 Measured Results

Level 1 of the CEC is located on the bottom level of the infrastructure section of the CEC. It is two levels below the stadium concourse. Entrances to this level are located at the ground level on the north side of the CEC.

We collected data on level 1 over the walk path described in Section 4.1. It should be noted that, on some of the walk tests, we were not able to test over waypoints 13–15 (Figure 168) because of a building improvement project that was started during the course of the testing. This section of the walk tests was blocked off and the walk path was not completely closed.

We performed measurements for the same coverage combinations that were used in the level 2 tests:

- PSCR MN only at 40 W

- COW only at 40 W
- COW at 40 W + PSCR MN
- SCDA only at 1 W
- SCDA at 1W + COW at 40 W
- SCDA at 1W + COW at 40 W + PSCR MN
- SCDA at 5 W + COW at 40 W + PSCR (Levels 1 and 2 only)

The first six coverage configurations are identical to the ones we used for the stadium tests. We added the last configuration to improve coverage with the SCDA at maximum power, deep in the interior of the infrastructure section.

The measured RSRP levels for a UDP downlink data flow are shown in Figures 211–217 for the seven coverage combinations. RSRP histograms for both UDP downlink and uplink data flows are plotted in Figures 218 and 219, and summary statistics are given in Tables 113 and 114. The PSCR MN signal does not penetrate well into level 1. The resulting signal levels are quite weak and network connectivity is marginal: 35% of the RSRP readings are below −120 dBm—a weak signal indeed! The median and maximum RSRP levels are −114 dBm and −99 dBm respectively for a downlink data flow. There are numerous disconnections and reconnections during the course of the walk test, indicative of a marginal link. The poor signal conditions are caused by the combination of the outer building walls, numerous interior walls, and the floors. In addition, level 1 is below grade on the southwest side of the CEC, which introduces additional RF attenuation. This is a difficult location for radio communications!

The situation improves when the COW provides coverage. Signal conditions increase over 75% of the walk path, with the greatest improvements on the northern part of the path closest to the COW. The resulting median RSRP values for a downlink data flow are −90 dBm and −70 dBm respectively. The western portion of the walk path experiences high levels of RF attenuation due to a large number of interior walls, and the signal levels remain below −110 dBm. Virtually no change is seen when the macro network is added to the coverage.

The SCDA (1 W) provides surprisingly good coverage on the southern portion of the walk path as is seen in Figure 214. Level 1 is connected directly to the stadium floor by a tunnel, which provides robust RF coupling into the south end of level 1. Weak signal levels occur at both the northern and westernmost portions of the path—due to high levels of interior RF attenuation. Adding the macro network to the SCDA has very little impact.

When the COW is operated in tandem with the SCDA at 1 W, much improved coverage results, as can be seen in Figure 216. In this case, the COW covers the northern portion of the walk path and the SCDA the southern part. Adding the macro network to the COW and SCDA coverage has a negligible impact on the RSRP results. The median and peak RSRP power levels for a downlink data flow are now −82 dBm and −63 dBm respectively. However, the westernmost portion of the walk path still remains at low signal levels. We do see some relief here when we increase the SCDA power level to the maximum of 5 W. The results of this are seen in Figure 217, in which improved signal levels are noted.

The CINR results for UDP downlink and uplink data flows with the PSCR MN are shown in Figures 220 and 221 respectively. The summary statics are given in Tables 115 and 116. Poor results are seen for both data flows with an observed range of −20 dB to +15 dB when coverage is provided by the PSCR MN. Significant improvements occur when the COW provides coverage, with typical increases of 15–20 dB in the CINR values. Adding the macro network to the coverage produces similar results. The best results are seen with the SCDA (at either 1 W or 5 W) and COW used in tandem. In all cases, the resulting spreads in CINR values are large due to the path loss variability between the UE and the serving cell.

The PDSCH downlink data rates are given in Figure 222 with summary statistics provided in Table 117. The median and peak down link rates with the PSCR MN are 1.9 Mb/s and 19.8 Mb/s. In this case, we see high counts of low data rates. Approximately 58% of the measured data rates are below 0.1 Mb/s—this due to low signal levels that occur over most of the walk path. The COW provides much better coverage with data rates in the range of 4–47 Mb/s. The COW yields median and peak data rates of 26 Mb/s and 47 Mb/s. The large spread of data rates is due to the large variation in path loss over the walk route. The SCDA system yields improved results as well with a median of 14 Mb/s and a peak of 48 Mb/s. When the COW is combined with the SCDA at 1 W, we see a similar level of improved performance with a peak data rate in excess of 50 Mb/s. The best overall median data rate performance of 32 Mb/s is realized with the combination of the SCDA at 5 W, the COW, and the PSCR MN, as can be seen in Figure 222 (g). For this coverage combination, 98% of the downlink rates exceed 5 Mb/s.

Results for PUSCH uplink data rates are plotted in Figure 223 and statistics are summarized in Table 118. Low data rates occur with the PSCR MN providing coverage, and 92% of the measured data rates are below 0.5 Mb/s. The resulting median and peak data rates are 0.1 Mb/s and 2.4 Mb/s respectively. In addition to the low data rates, numerous disconnections and reconnections occur over the walk path.

The COW provides much improved performance with solid connectivity throughout the walk test. The median uplink data rate increases to 12 Mb/s and a peak rate of 17 Mb/s. In this case, 76% of the measured data rates are greater than 5 Mb/s. We see similar results when the macro network is added to the coverage. The SCDA (1 W) gives good performance, with 62% of the uplink data rates in excess of 5 Mb/s.

The combined coverage of the COW and the SCDA at 1 W produces even better results with 90% of the uplink data rates in excess of 5 Mb/s. The addition of the macro network to the coverage lowers data rates due to disconnections and reconnections that occur during the walk. The combination of the COW and SCDA at 5 W produces connection problems over the northern portion of the walk route due to multiple handovers between the COW and the small cell. This issue accounts for the more frequent occurrences of low data rates. Network optimization would be needed to correct this problem.

The UE transmit power levels for UDP downlink and uplink data flows are plotted in Figures 224 and 225 respectively. Summary statistics are provided in Tables 119 and 120. When the macro network provides coverage, the UE operates near its maximum operating power level of +23 dBm over the entire walk route for both downlink and uplink data flows. High path losses between the Green Mountain eNB and the UE force a maximum transmit power level for both uplink and downlink data flows.

The situation improves when the COW is the source of coverage. The UE is now able to transmit at lower power levels over the northern portion of the walk path that is closest to the COW. However, high UE transmit power levels are still seen for the parts of the walk path deep inside the building, where the RF attenuation is high. The addition of the PSCR MN to the COW for coverage has a minimal effect, and the resulting distributions are similar.

The best overall downlink data flow results are obtained when the SCDA (1 W) is providing coverage. Adding the COW and the macro network to the coverage produces higher UE power levels, due to neighbor cell interference effects. The picture is a bit different for an uplink data flow, where improved performance is seen with combined coverage of the SCDA (1W) and the COW.

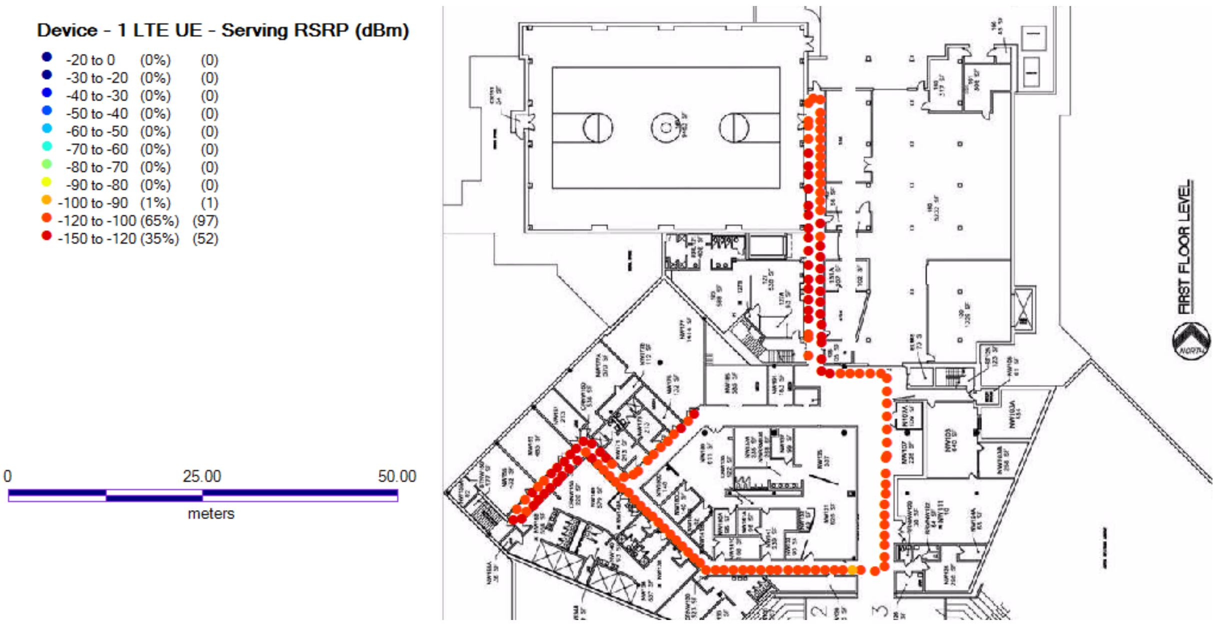

Figure 211. CEC level 1 reference signal received power (RSRP) for a UDP downlink data flow with the PSCR MN 40 W. The path is not closed due to a construction project that occurred at the time of the test. North is at the top of the figure.

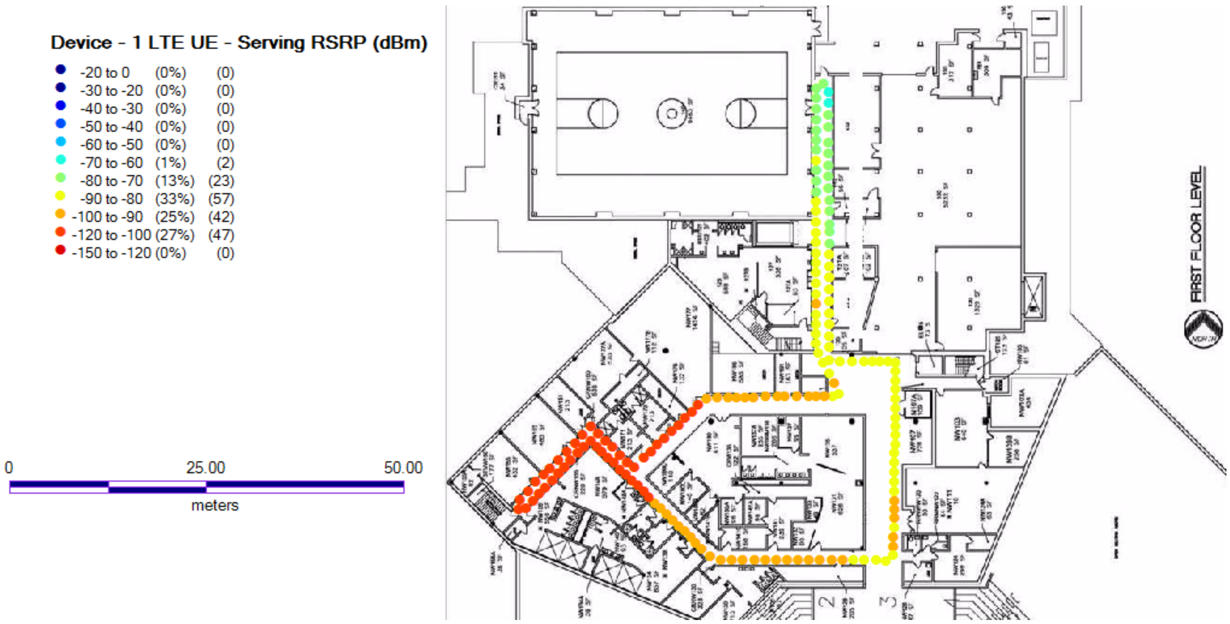

Figure 212. CEC level 1 reference signal received power (RSRP) for a UDP downlink data flow with the COW at 40 W. North is at the top of the figure.

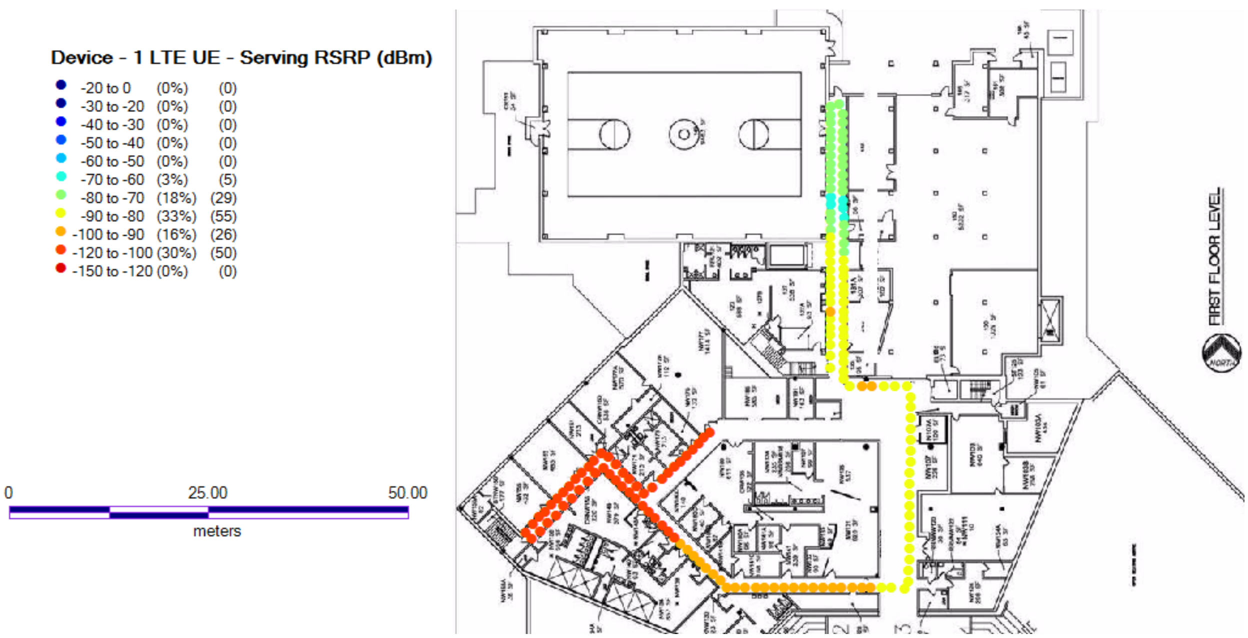

Figure 213. CEC level 1 reference signal received power (RSRP) for a UDP downlink data flow with the COW at 40 W and the PSCR MN. The path is not closed due to a construction project that occurred at the time of the test. North is at the top of the figure.

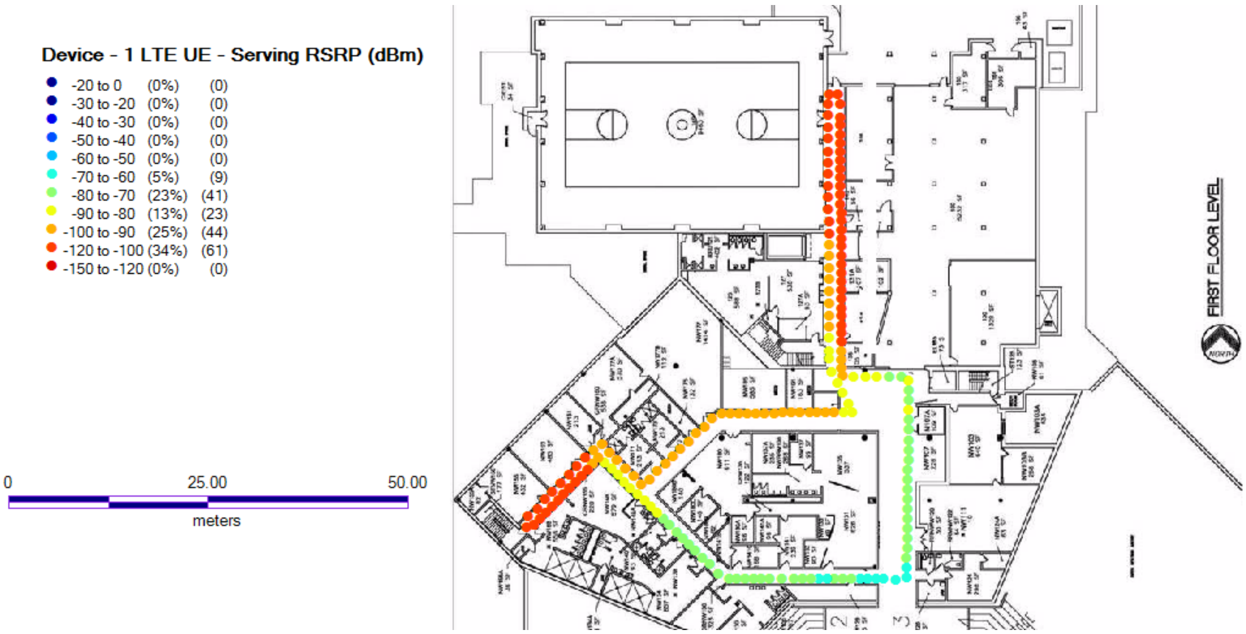

Figure 214. CEC level 1 reference signal received power (RSRP) for a UDP downlink data flow with the SCDA at a transmit power of 1 W. North is at the top of the figure.

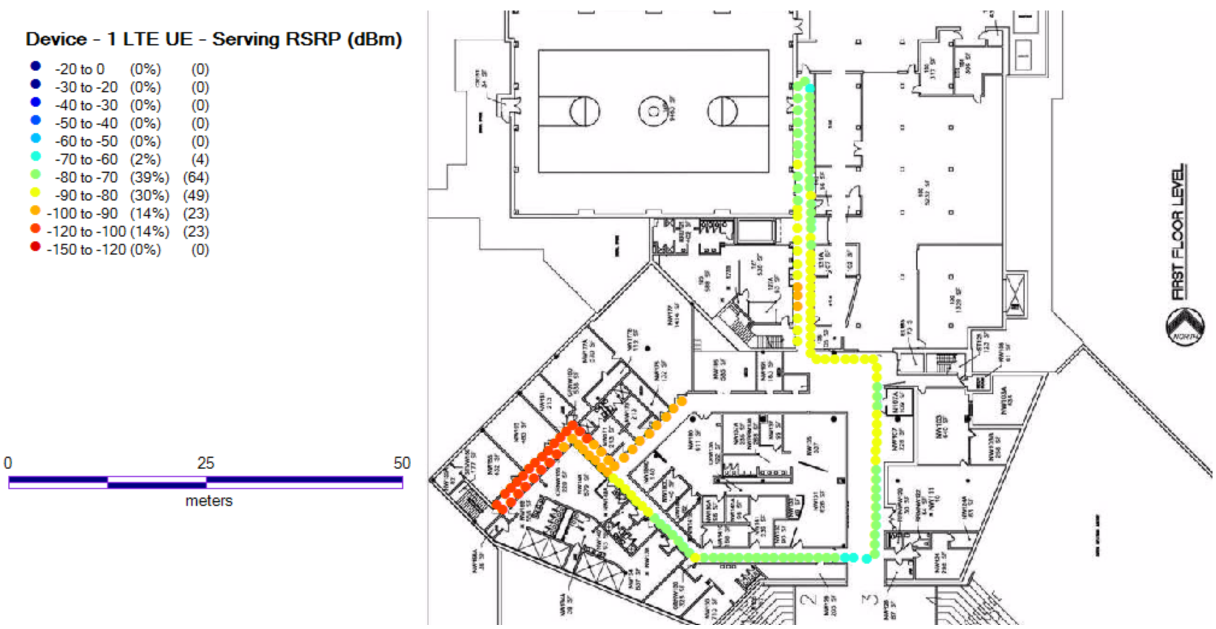

Figure 215. CEC level 1 reference signal received power (RSRP) for a UDP downlink data flow with the SCDA at a transmit power of 1 W and a COW at 40 W. The path is not closed due to a construction project that occurred at the time of the test. North is at the top of the figure.

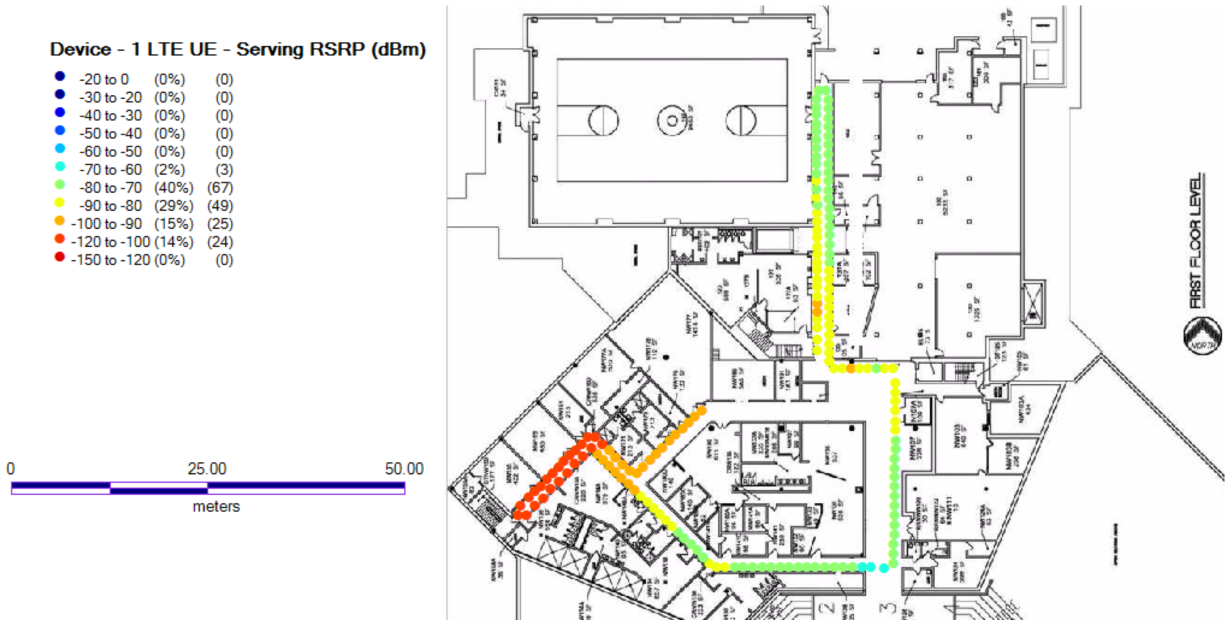

Figure 216. CEC level 1reference signal received power (RSRP) for a UDP downlink data flow with the SCDA at a transmit power of 1 W and a COW at 40 W and the PSCR MN. The path is not closed due to a construction project that occurred at the time of the test. North is at the top of the figure.

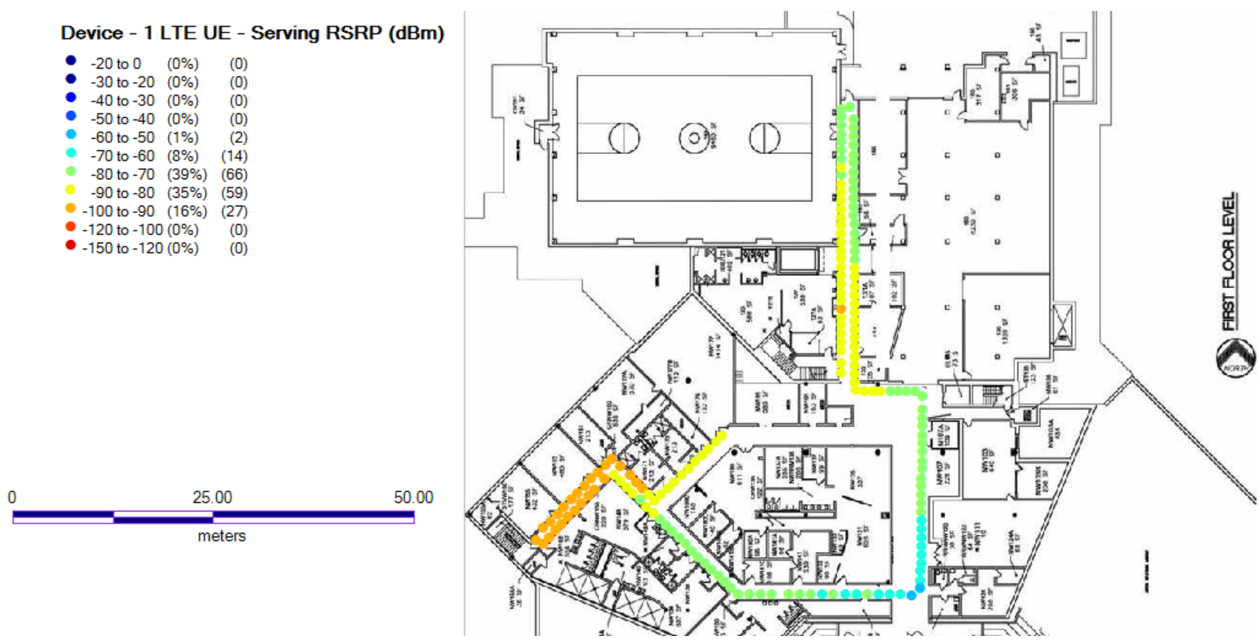

Figure 217. CEC level 1 reference signal received power (RSRP) for a UDP downlink data flow with the SCDA at the maximum transmit power of 5 W and a COW at 40 W. Note the improved coverage in the office section (left side of the figure). The path is not closed due to a construction project that occurred at the time of the test. North is at the top of the figure.

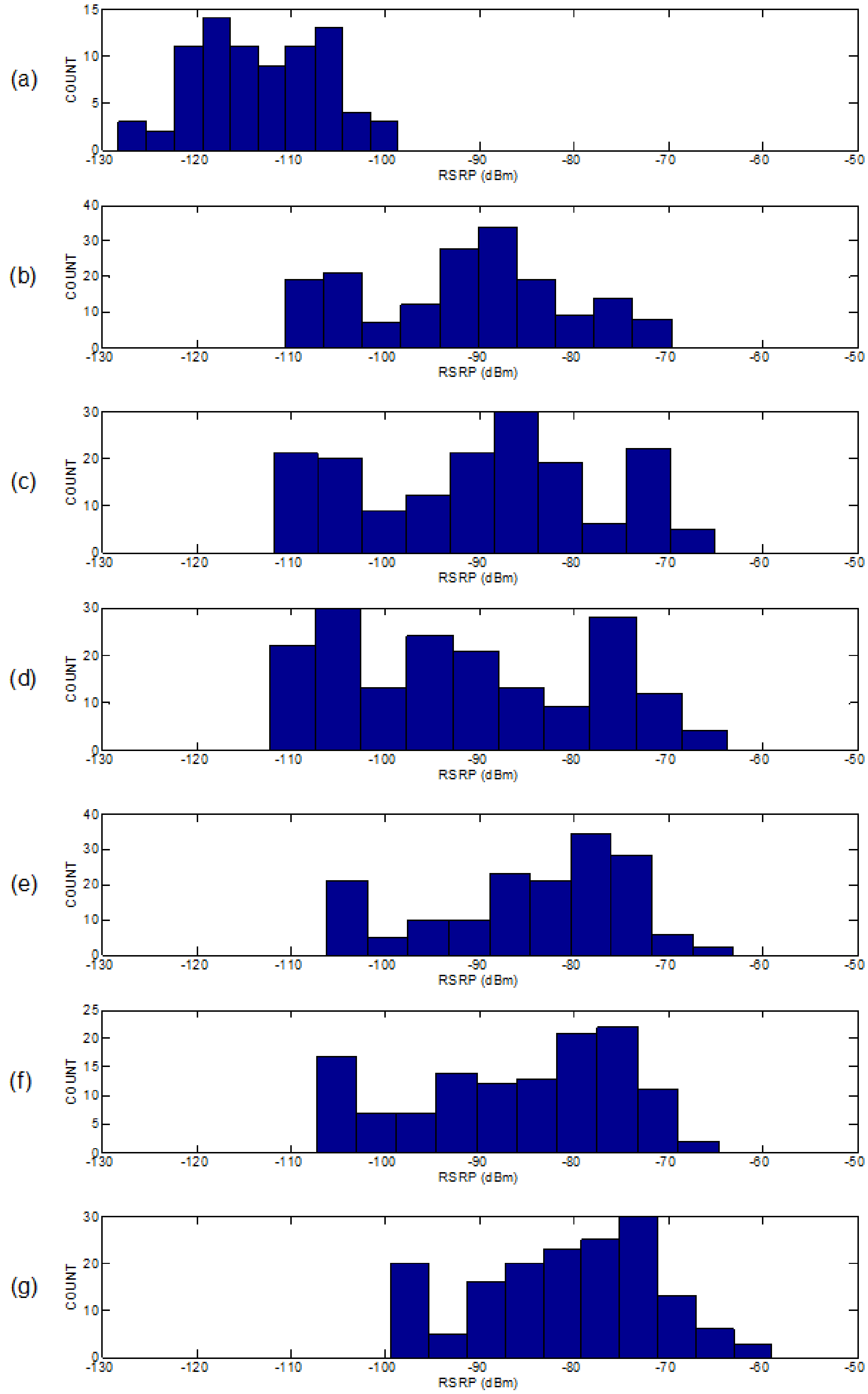

Figure 218. CEC level 1 histograms of RSRP for different coverage combinations with a UDP downlink data flow. (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN, (g) SCDA at a maximum power level of 5 W and COW at 40 W.

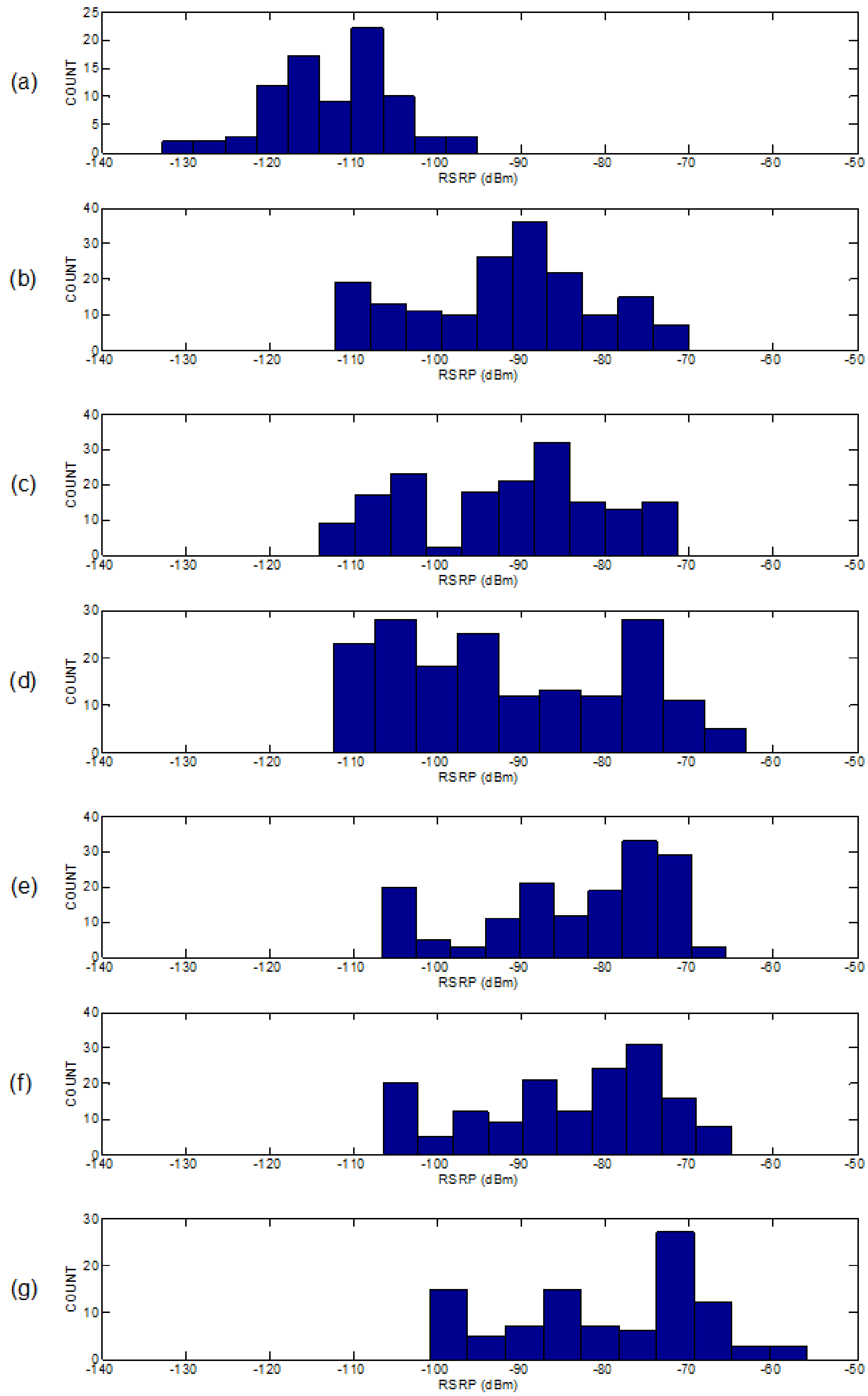

Figure 219. CEC level 1 histograms of RSRP for different coverage combinations with a UDP uplink data flow. (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN, (g) SCDA at a maximum power level of 5 W and COW at 40 W.

Table 113. CEC level 1 RSRP statistics for a UDP downlink data flow.

Coverage Combination	Mean RSRP (dBm)	Median RSRP (dBm)	Standard Deviation (dBm)	Min RSRP (dBm)	Max RSRP (dBm)
PSCR MN	-113.3	-113.6	6.8	-128.3	-98.6
COW 40 W	-91.5	-90.3	10.6	-110.6	-69.7
PSCR MN + COW 40 W	-90.4	-88.5	12.7	-111.9	-65.1
SCDA 1 W	-91.5	-93.3	13.1	-112.3	-63.7
SCDA 1 W + COW 40 W	-84.7	-82.4	10.6	-106.3	-63.1
SCDA 1 W + COW 40 W + PSCR MN	-86.4	-84.7	11.2	-107.4	-64.7
SCDA 5 W + COW 40 W + PSCR MN	-80.9	-80.1	9.6	-99.4	-59.0

Table 114. CEC level 1 RSRP statistics for a UDP uplink data flow.

Coverage Combination	Mean RSRP (dBm)	Median RSRP (dBm)	Standard Deviation (dBm)	Min RSRP (dBm)	Max RSRP (dBm)
PSCR MN	-112.4	-111.6	7.3	-132.9	-95.3
COW 40 W	-91.6	-89.8	10.8	-112.3	-70.0
PSCR MN + COW 40 W	-91.9	-89.2	11.5	-114.2	-71.4
SCDA 1 W	-91.5	-93.4	13.5	-112.5	-63.3
SCDA 1 W + COW 40 W	-83.6	-80.0	11.1	-106.7	-65.6
SCDA 1 W + COW 40 W + PSCR MN	-84.5	-81.7	11.3	-106.5	-65.0
SCDA 5 W + COW 40 W + PSCR MN	-79.7	-77.1	11.6	-100.9	-56.0

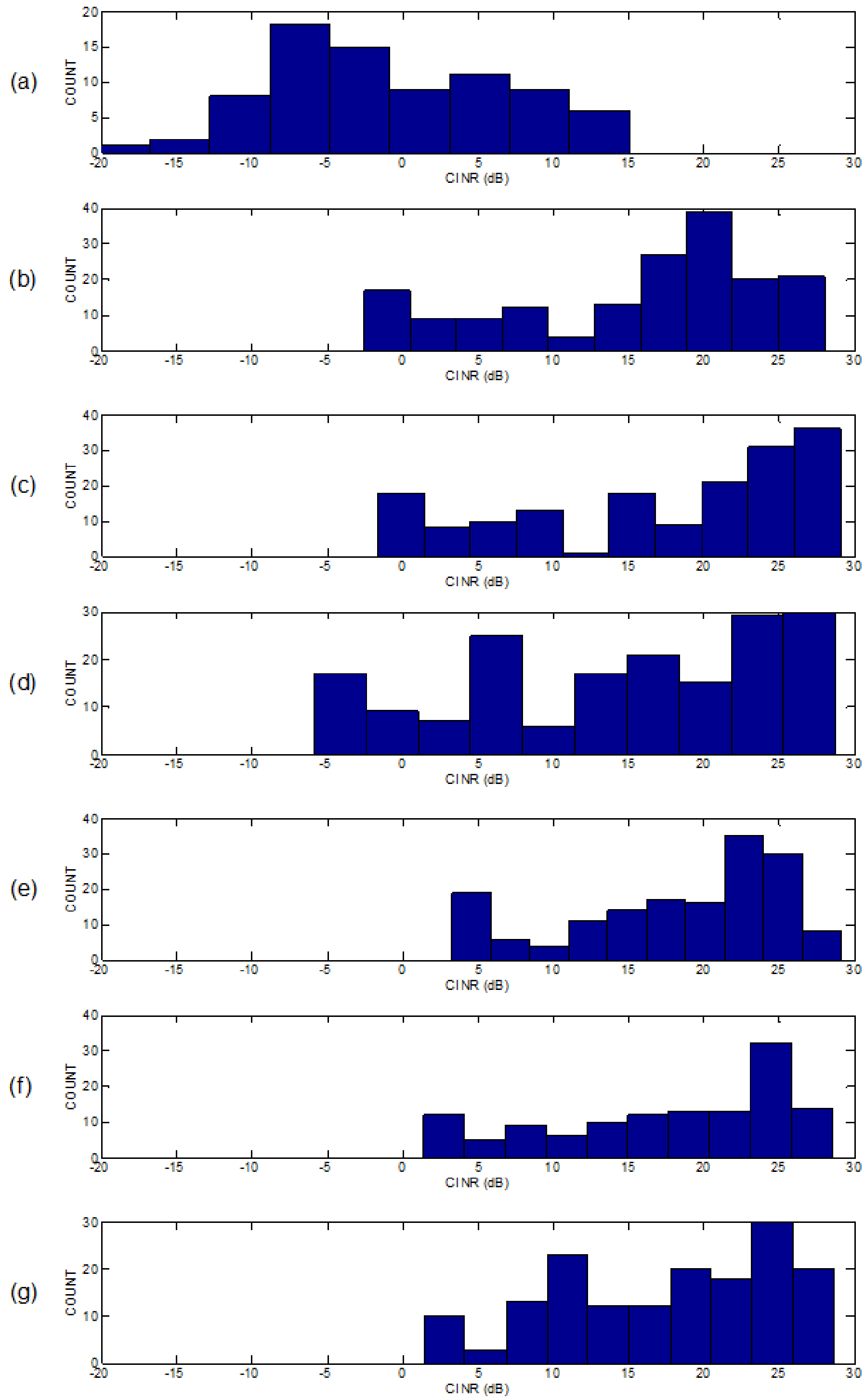

Figure 220. CEC level 1 histograms of CINR for different coverage combinations with a UDP downlink data flow, (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN, (g) SCDA at a maximum power level of 5 W and COW at 40 W.

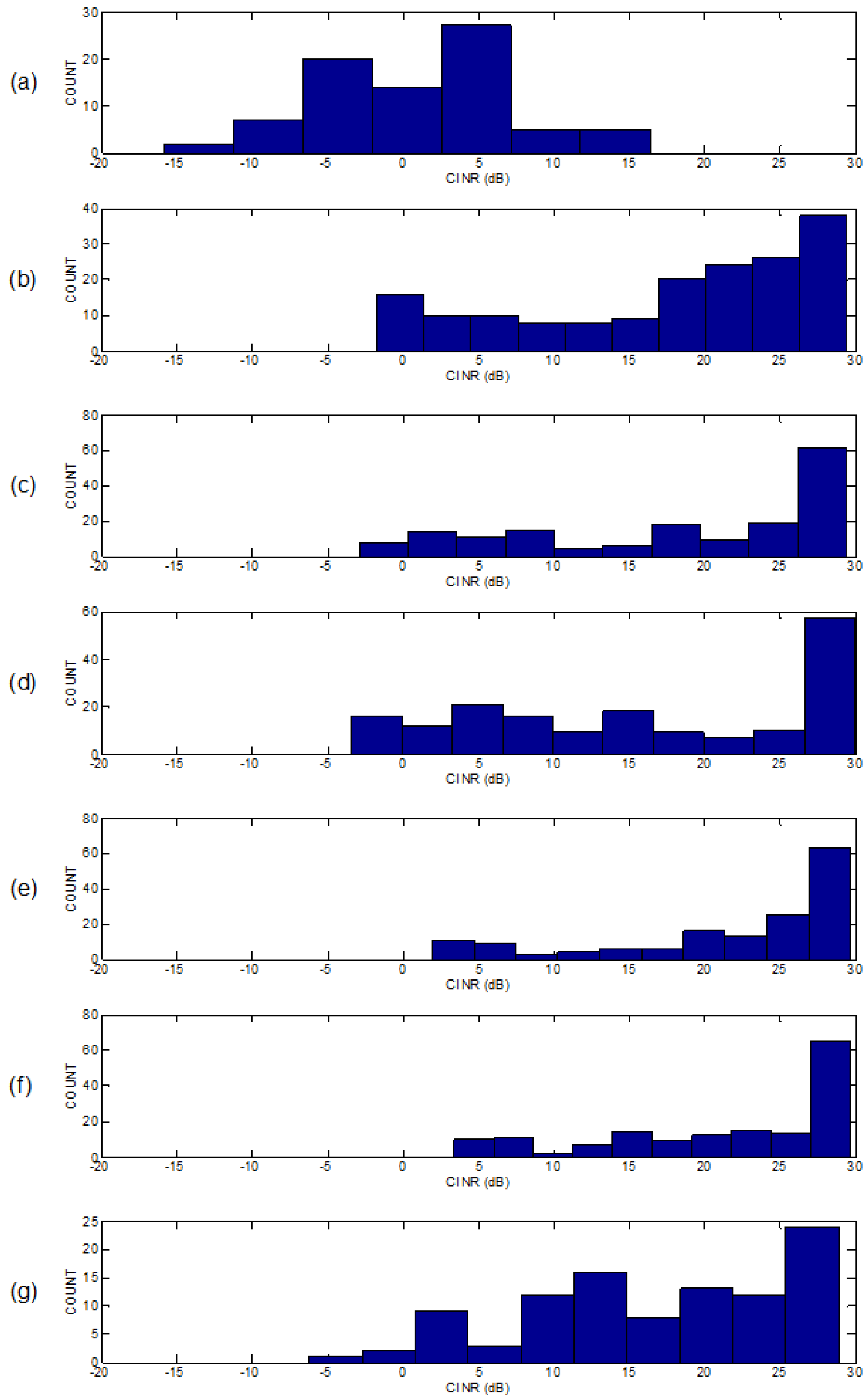

Figure 221. CEC level 1 histograms of CINR for different coverage combinations with a UDP uplink data flow, (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN, (g) SCDA at a maximum power level of 5 W and COW at 40 W.

Table 115. CEC level 1 CINR statistics for a UDP downlink data flow.

Coverage Combination	Mean CINR (dB)	Median CINR (dB)	Standard Deviation (dB)	Min CINR (dB)	Max CINR (dB)
PSCR MN	-1.7	-2.2	8.5	-24.8	15.1
COW 40 W	15.5	17.6	8.8	-2.6	28.0
PSCR MN + COW 40 W	17.3	20.6	9.6	-1.6	29.1
SCDA 1 W	14.4	15.6	10.2	-5.9	28.8
SCDA 1 W + COW 40 W	18.1	20.2	7.2	3.3	29.1
SCDA 1 W + COW 40 W + PSCR MN	17.6	20.0	7.8	1.4	28.5
SCDA 5 W + COW 40 W + PSCR MN	17.6	19.6	7.3	1.4	28.7

Table 116. CEC level 1 CINR statistics for a UDP uplink data flow.

Coverage Combination	Mean CINR (dB)	Median CINR (dB)	Standard Deviation (dB)	Min CINR (dB)	Max CINR (dB)
PSCR MN	0.2	1.3	8.3	-29.7	16.4
COW 40 W	17.8	20.7	9.6	-1.7	29.4
PSCR MN + COW 40 W	18.5	22.0	10.3	-2.9	29.4
SCDA 1 W	16.0	16.3	10.9	-3.4	30.0
SCDA 1 W + COW 40 W	21.8	25.6	8.3	1.9	29.7
SCDA 1 W + COW 40 W + PSCR MN	21.3	24.0	8.0	3.4	29.7
SCDA 5 W + COW 40 W + PSCR MN	17.0	17.3	8.8	-6.3	28.9

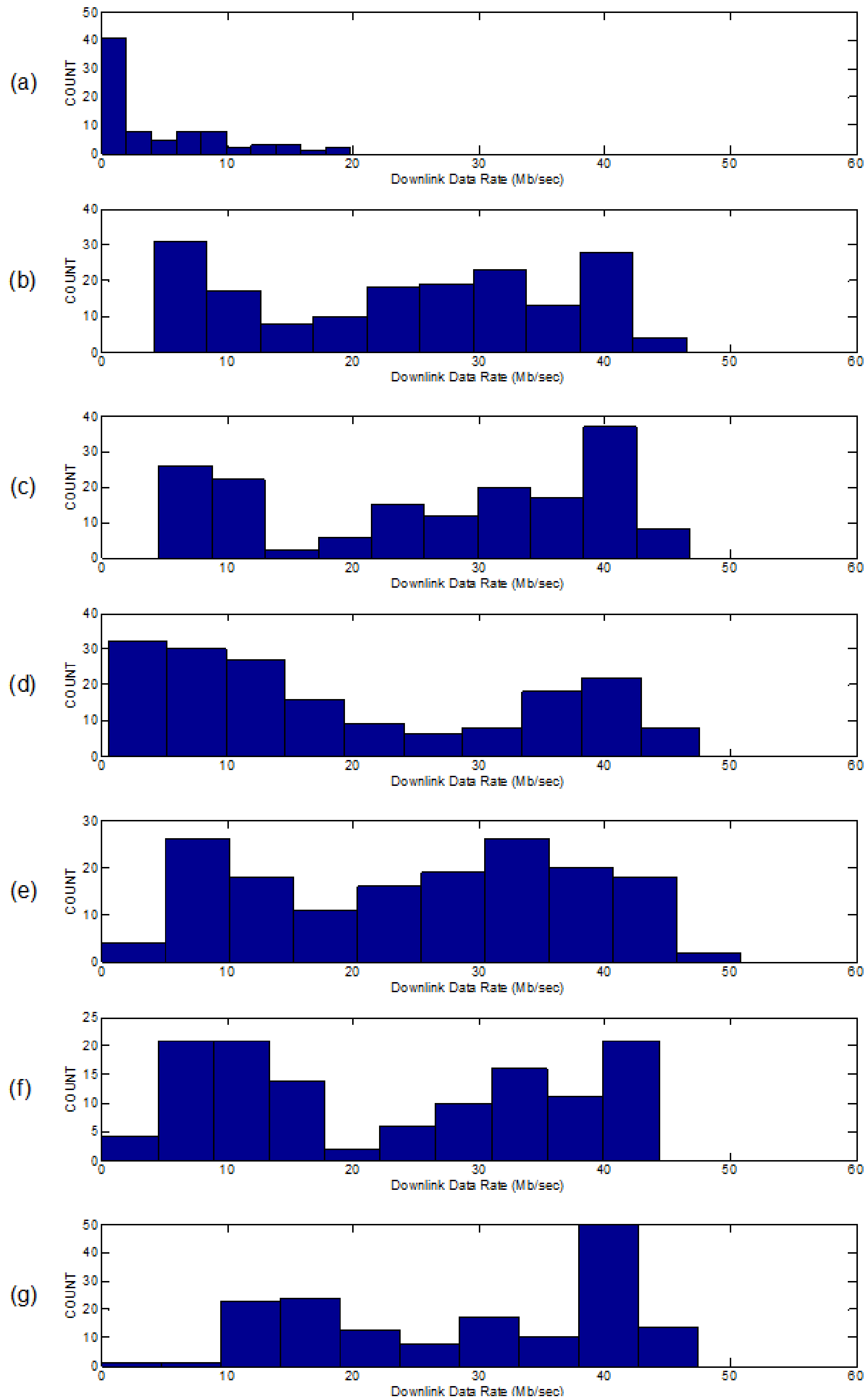

Figure 222. CEC level 1 histograms of PDSCH downlink data rates for different coverage configurations with a UDP downlink data flow. (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN, (g) SCDA at a maximum power level of 5 W and COW at 40 W.

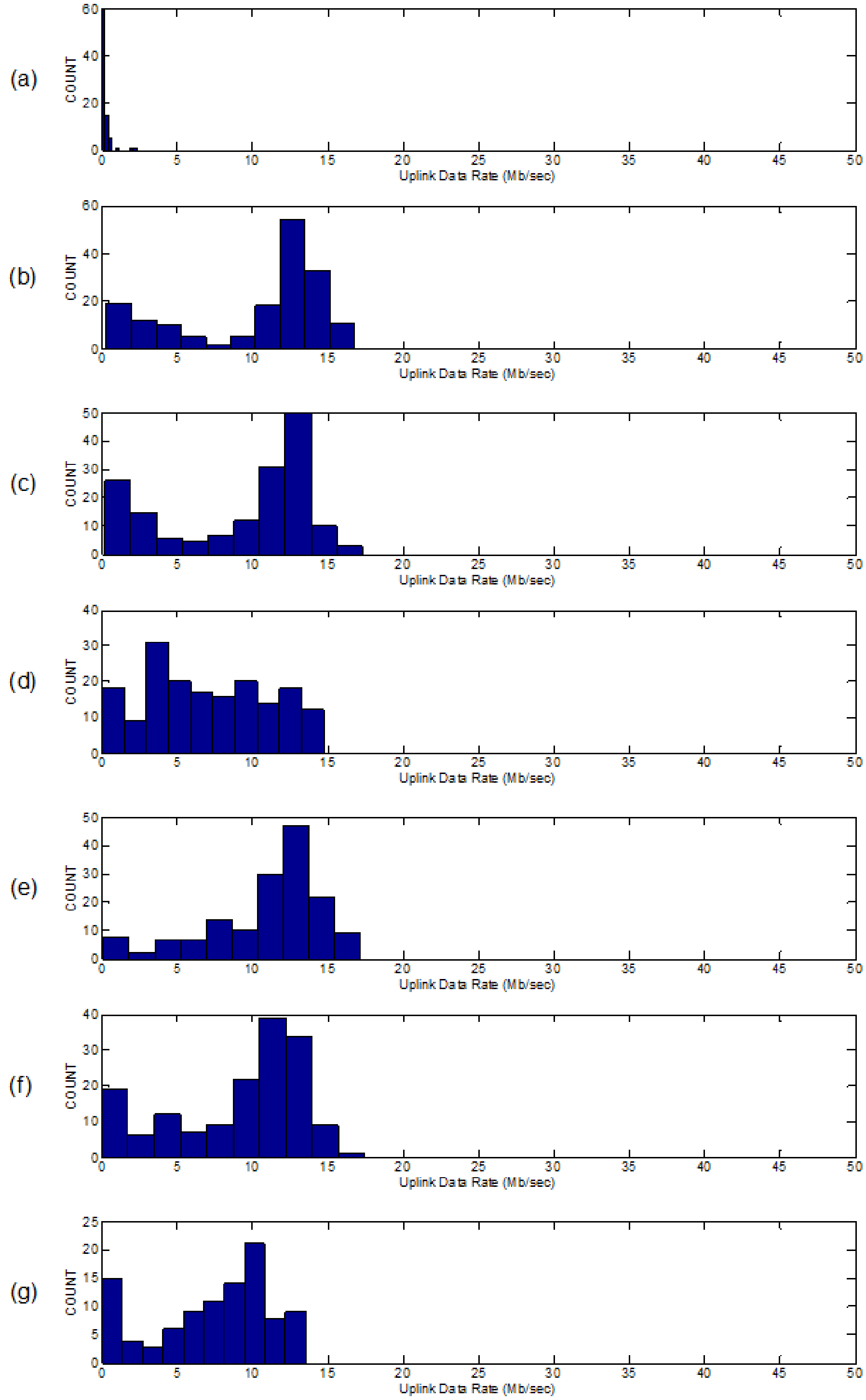

Figure 223. CEC level 2 histograms of PUSCH uplink data rates for different coverage configurations with a UDP uplink data flow. (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN, (g) SCDA at a maximum power level of 5 W and COW at 40 W.

Table 117. CEC level 1 PDSCH statistics for a UDP downlink data flow.

Coverage Combination	**Mean PDSCH (Mb/s)**	**Median PDSCH (Mb/s)**	**Standard Deviation (Mb/s)**	**Min PDSCH (Mb/s)**	**Max PDSCH (Mb/s)**
PSCR MN	4.3	1.9	5.1	0.0	19.8
COW 40 W	24.1	25.5	12.7	4.1	46.5
PSCR MN + COW 40 W	26.4	29.8	13.4	4.5	46.7
SCDA 1 W	19.4	14.4	14.2	0.5	47.5
SCDA 1 W + COW 40 W	25.1	27.4	12.9	0.1	50.8
SCDA 1 W + COW 40 W + PSCR MN	23.1	23.2	13.6	0.0	44.3
SCDA 5 W + COW 40 W + PSCR MN	29.3	31.9	12.1	0.0	47.4

Table 118. CEC level 1 PUSCH statistics for a UDP uplink data flow.

Coverage Combination	**Mean PUSCH (Mb/s)**	**Median PUSCH (Mb/s)**	**Standard Deviation (Mb/s)**	**Min PUSCH (Mb/s)**	**Max PUSCH (Mb/s)**
PSCR MN	0.2	0.1	0.4	0.0	2.4
COW 40 W	10.2	12.4	4.88	0.3	16.8
PSCR MN + COW 40 W	9.0	11.4	5.0	0.2	17.3
SCDA 1 W	7.0	6.6	4.0	0.0	14.7
SCDA 1 W + COW 40 W	10.9	12.1	3.9	0.1	17.1
SCDA 1 W + COW 40 W + PSCR MN	9.0	10.7	4.4	0.0	17.4
SCDA 5 W + COW 40 W + PSCR MN	7.4	8.3	3.9	0.0	13.5

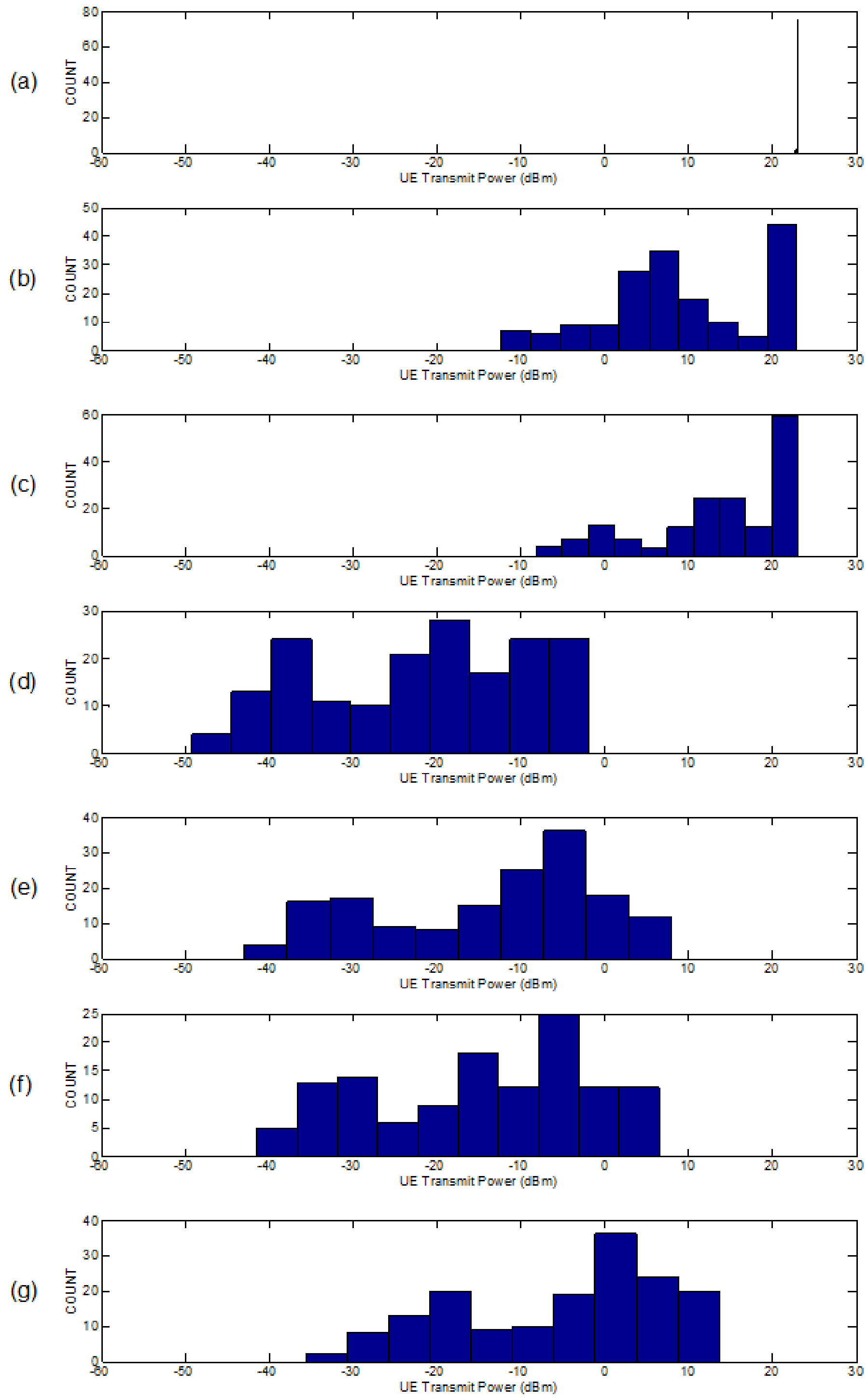

Figure 224. CEC level 2 histograms of UE transmit power for different coverage configurations with UDP downlink data flow. (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN, (g) SCDA at a maximum power level of 5 W and COW at 40 W.

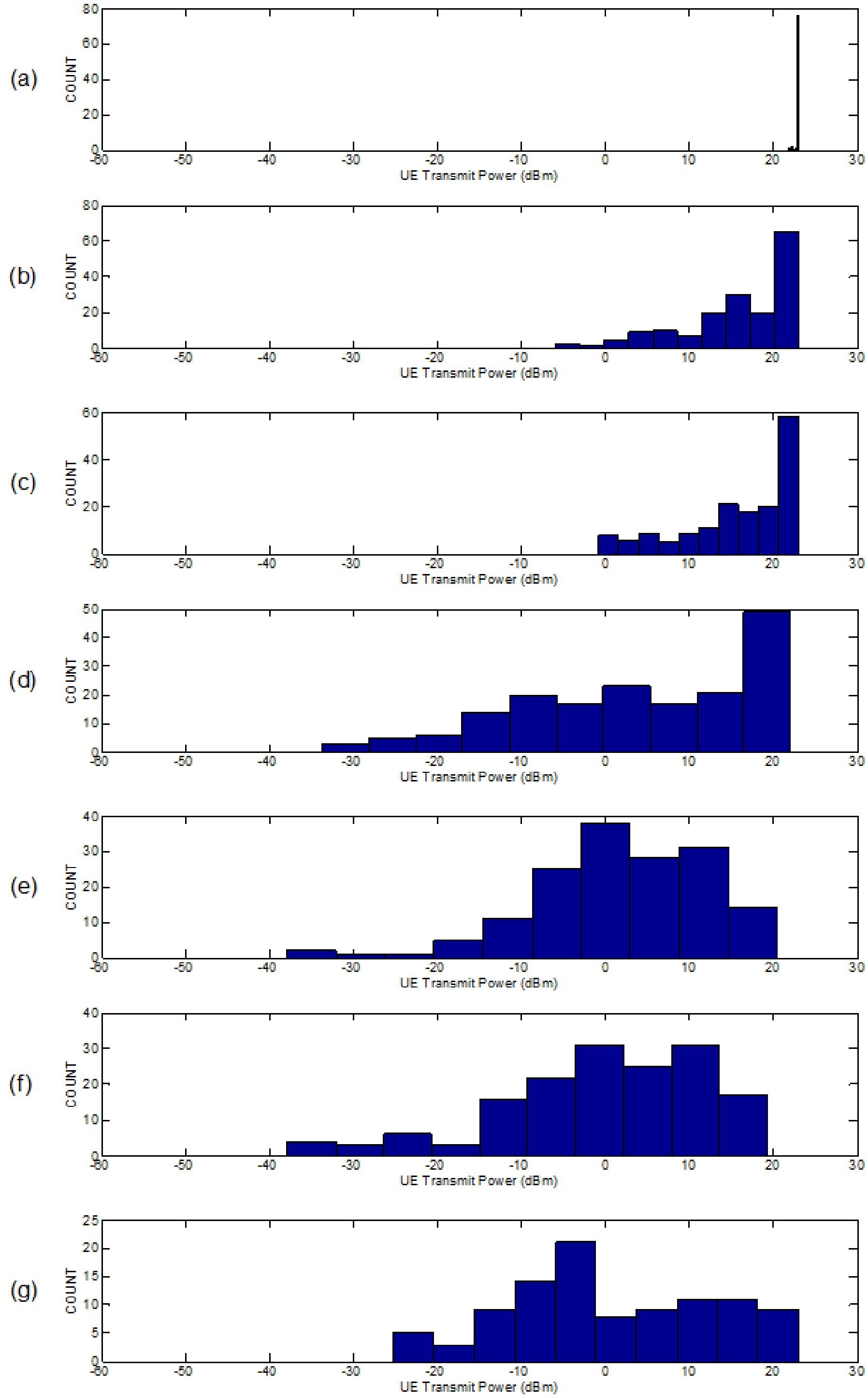

Figure 225. CEC level 2 histograms of UE transmit power for different coverage configurations with UDP uplink data flow. (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN, (g) SCDA at a maximum power level of 5 W and COW at 40 W.

Table 119. CEC level 1 UE transmit power statistics for a UDP downlink data flow.

Coverage Combination	Mean UE tpwr (dBm)	Median UE tpwr (dBm)	Standard Deviation (dBm)	Min UE tpwr (dBm)	Max UE tpwr (dBm)
PSCR MN	23.0	23.0	0.1	22.6	23.0
COW 40 W	9.3	8.0	9.5	-12.4	22.9
PSCR MN + COW 40 W	13.9	15.3	8.9	-8.2	23.0
SCDA 1 W	-21.7	-20.3	12.8	-49.3	-1.9
SCDA 1 W + COW 40 W	-13.8	-9.8	13.1	-43.0	7.9
SCDA 1 W + COW 40 W + PSCR MN	-14.8	-13.2	12.6	-41.5	6.4
SCDA 5 W + COW 40 W + PSCR MN	-5.2	-1.8	12.5	-35.7	13.6

Table 120. CEC level 1 UE transmit power statistics for a UDP uplink data flow.

Coverage Combination	Mean UEpwr (dBm)	Median UE tpwr (dBm)	Standard Deviation (dBm)	Min UEpwr (dBm)	Max UEpwr (dBm)
PSCR MN	22.9	23.0	0.2	21.8	23.0
COW 40 W	16.0	17.4	6.5	-5.9	23.0
PSCR MN + COW 40 W	15.8	17.6	6.8	0.9	23.0
SCDA 1 W	3.9	5.0	14.5	-33.8	22.0
SCDA 1 W + COW 40 W	1.9	2.3	10.3	-38.0	20.5
SCDA 1 W + COW 40 W + PSCR MN	-0.4	1.2	12.2	-37.9	19.3
SCDA 5 W + COW 40 W + PSCR MN	0.6	-1.5	12.1	-25.3	23.0

5.4 CEC Outdoor Measured Results

This section summarizes measurements obtained outside the CEC. We have several reasons for taking these measurements. First, we want quantify the signal levels and associated LTE system performance for those systems that provide external RF coverage: the PSCR MN and the COW. Second, we would like to quantify how much RF energy produced by the SCDA system leaks out of the building. Finally, we examine the interplay between the interior and exterior coverage systems when combinations of these systems are active.

We collected data over the outdoor walk paths described in Section 4.1. We performed measurements with UDP uplink or downlink data flows for the following coverage combinations:

- PSCR MN only at 40 W
- COW only at 40 W

- COW at 40 W + PSCR MN
- SCDA only at 1 W
- SCDA at 1W + COW at 40 W
- SCDA at 1W + COW at 40 W + PSCR MN

These six combinations are identical to those used in all of the interior testing in the CEC.

Figures 226–231 show the RSRP results plotted on an aerial diagram of the CEC. Each plot contains two walk paths: 1) the short walk path on the north side of the CEC that faces the COW, and 2) the more extended walk path that is on the outdoor concourse and approximately 75% of the outer perimeter of the CEC. The corresponding RSRP histograms are shown in Figures 232 and 233 for UDP downlink and uplink data flows respectively. The histograms contain data for both walk paths. The associated summary statistics are compiled in Tables 121 and 122.

When the macro network provides coverage, 61% of the measured RSRP values lie in the range between −90 dBm and −80 dBm. The median and peak RSRP values are −84 dBm and −72 dBm respectively. This is approximately a 10 dB improvement in signal levels over what we saw in the stadium, approximately a 20 dB improvement over the levels we see on level 2, and approximately 30 dB more than the level 1 values.

The COW produces very strong signals on the north side of the CEC, but reduced levels on the upper concourse, due to blockage by the infrastructure section of the CEC. In this case, 53% of the measured RSRP levels lie in the range of −80 dBm to −50 dBm—the large spread is due to path loss variations over the walk route. The resulting median and maximum RSRP levels are −79 dBm and −47 dBm. The strong signal levels seen on the north side of the CEC and the reduced signals of the upper concourse produce the distinct bimodal structure of the histograms of Figures 232(b) and 233(b). Combining the COW with the PSCR MN yields similar distributions to those of the COW, but the minimum RSRP levels shift up approximately 10 dB, due to improved coverage on the upper concourse of the CEC.

The received RSRP with the SCDA (1 W) providing interior coverage is shown in Figure 229 for the upper concourse only. (We could not achieve connectivity on the north side of the CEC due to poor signal conditions). There is significant leakage on the west, south, and east sides since there are doors at these locations. Although the doors are all metal without windows, there is significant leakage through the door seams. The resulting RSRP histograms are shown in Figures 232(d) and 233(d). It is interesting that the histograms have a similar shape to those obtained with the macro network but with somewhat lower signal levels.

The results of adding the COW to the coverage are shown in Figure 230, and the corresponding distributions are shown in Figures 232(e) and 233(e). The higher count of increased signal levels can be attributed to measurements on the north side of the CEC, where the COW is located. Combining both the COW and the PSCR MN with the SCDA at 1 W yields the results shown in Figure 231. The macro network improves coverage on the southeast side of the CEC, and the spreads in the resulting distributions are reduced as is seen in Figures 232(f) and 233(f) for UDP downlink and uplink data flows respectively.

The CINR histograms obtained for various combinations of coverage are shown in Figures 234 and 235 for UDP downlink and uplink data flows respectively. The associated summary statistics are provided in Tables 123 and 124. The macro network yields more centralized distributions with lower spreads of data than other coverage types. This is due to the larger standoff distance and high location of the Green Mountain eNB relative to the location of CEC that results in more uniform RF coverage. The best CINR performance is seen for a UDP downlink data flow and coverage provided by the COW and the SCDA. The resulting median and maximum levels are 24 dB and 29 dB respectively. Interestingly, the COW provides the best performance for an uplink data flow with a median value of 28 dB and a maximum of 30 dB.

The PDSCH results are summarized in the histograms of Figure 236 and Table 125. The median downlink data rates are all high and network performance is good. Maximum data rates vary somewhat with the coverage configuration, and we see values in the range of 42–56 Mb/s.

The PUSCH uplink data rates are summarized in the histograms of Figure 237 and in Table 126. The story is quite similar to the downlink case. The median values are once again high with maximum values in the range 15–19 Mb/s.

The UE transmit power levels are summarized in Figures 238 and 239 for downlink and uplink data flows. The corresponding statistical summaries are shown in Tables 127 and 128. The variations of the UE transmit power distributions, with respect to the coverage combination, are complex. Using the PSCR MN as the sole source of coverage places the heaviest demands on the UE transmit power. All of the other coverage combinations reduce UE transmit power levels over portions of the walk path.

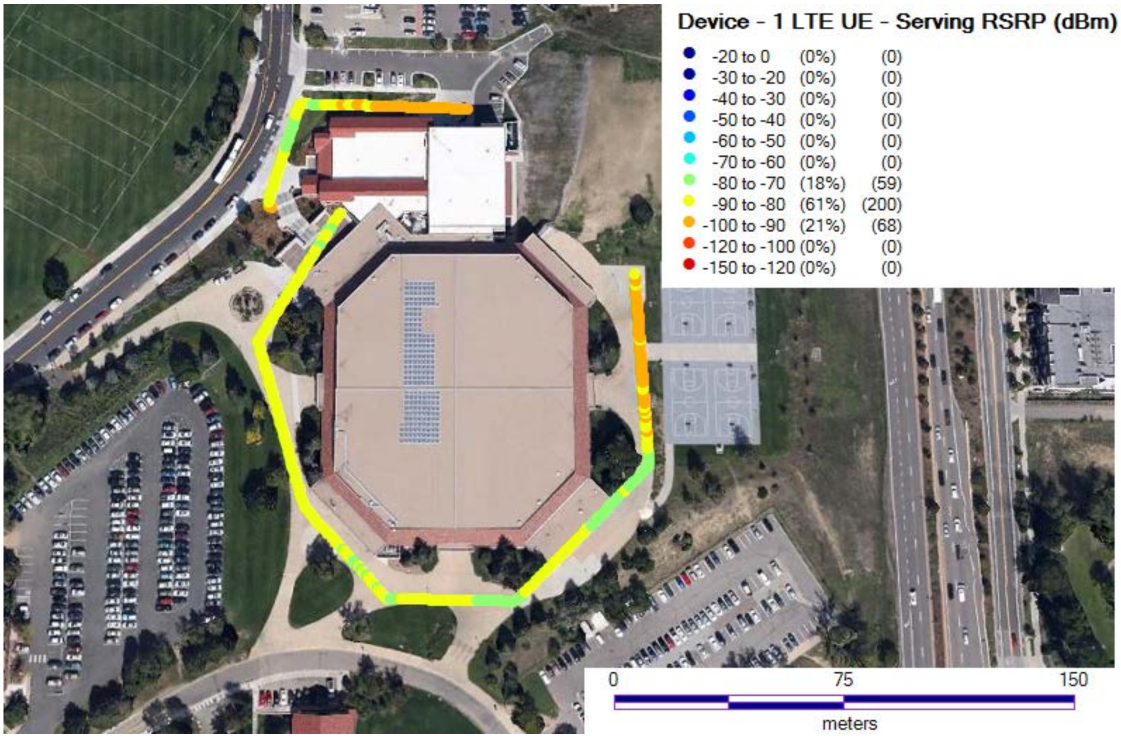

Figure 226. CEC Stadium (UDP downlink) reference signal received power (RSRP) with the PSCR MN at 40 W.

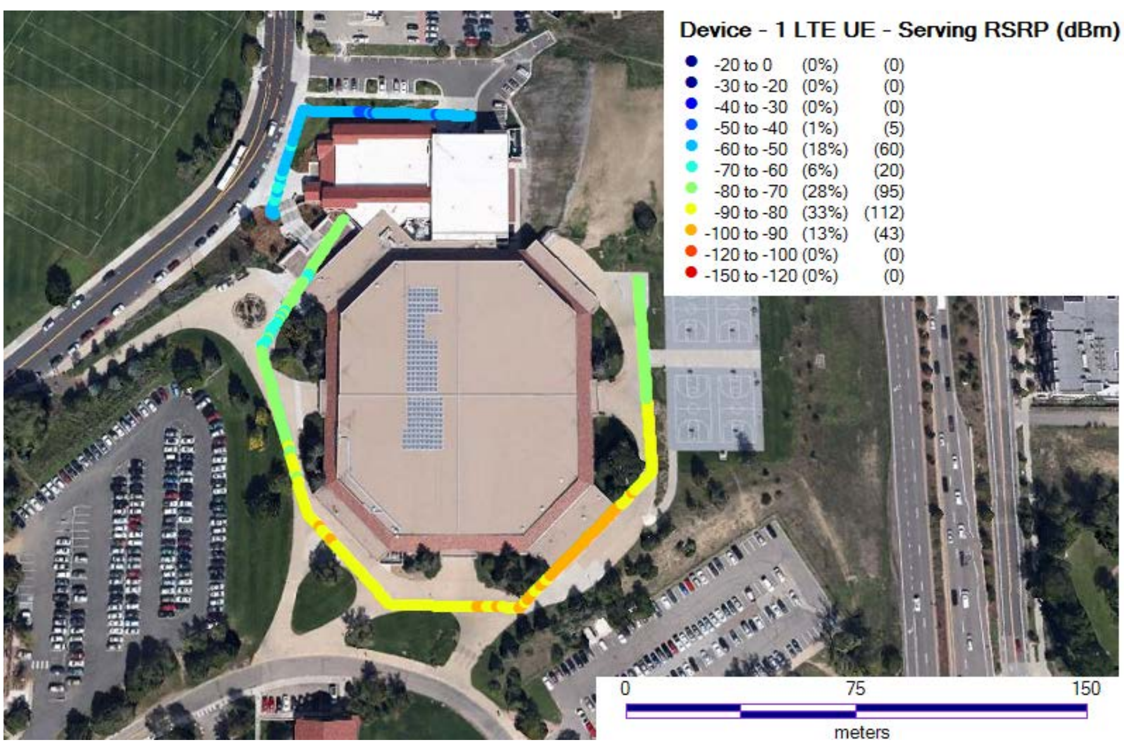

Figure 227. CEC outside (UDP downlink) reference signal received power (RSRP) with the COW at 40 W.

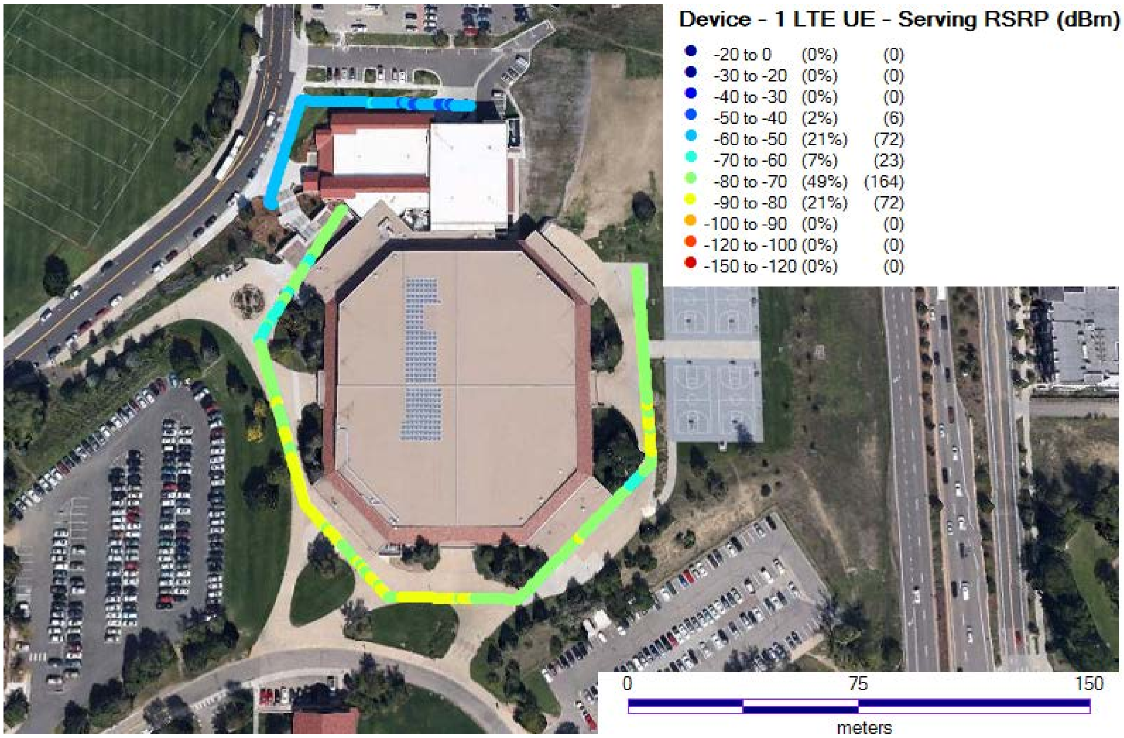

Figure 228. CEC outside (UDP downlink) reference signal received power (RSRP) with the COW at 40 W and the PSCR MN.

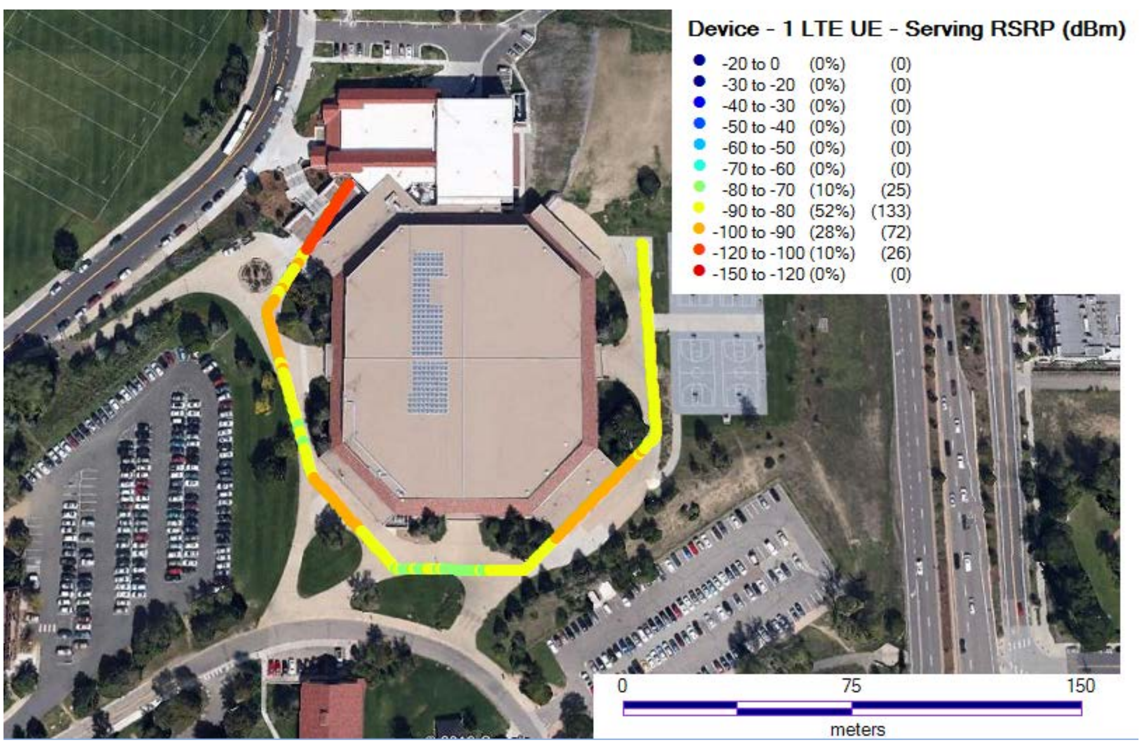

Figure 229. CEC outside (UDP downlink) reference signal received power (RSRP) with the SCDA at a transmit power of 1 W.

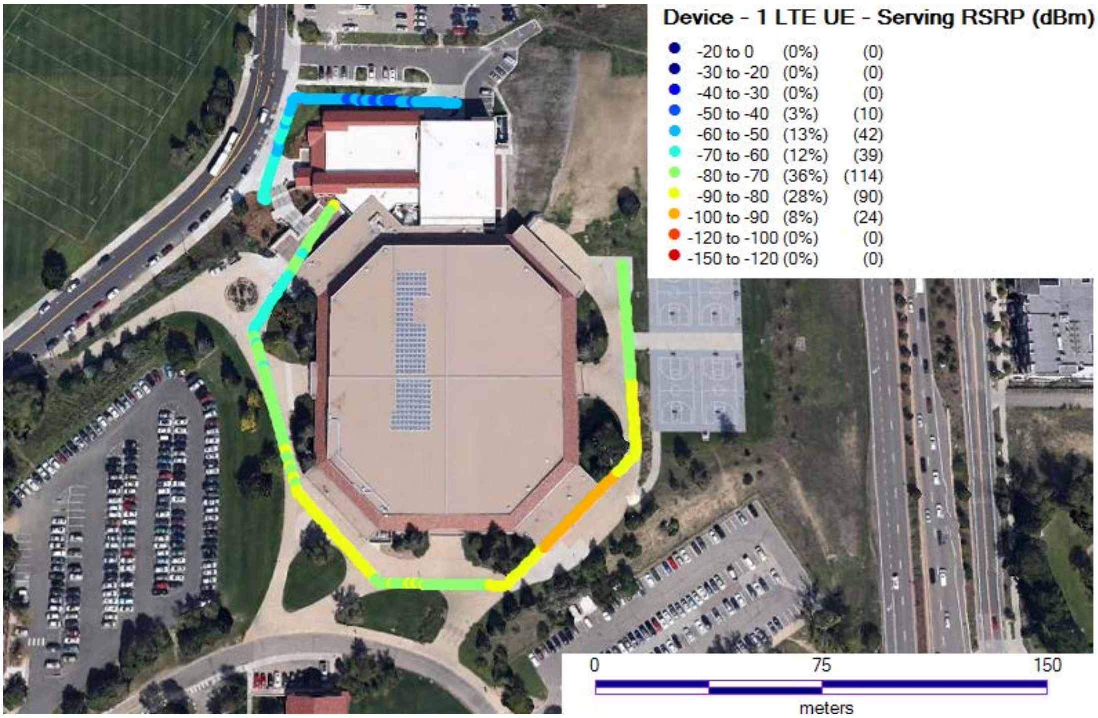

Figure 230. CEC outside (UDP downlink) reference signal received power (RSRP) with the SCDA at a transmit power of 1 W and a COW at 40 W.

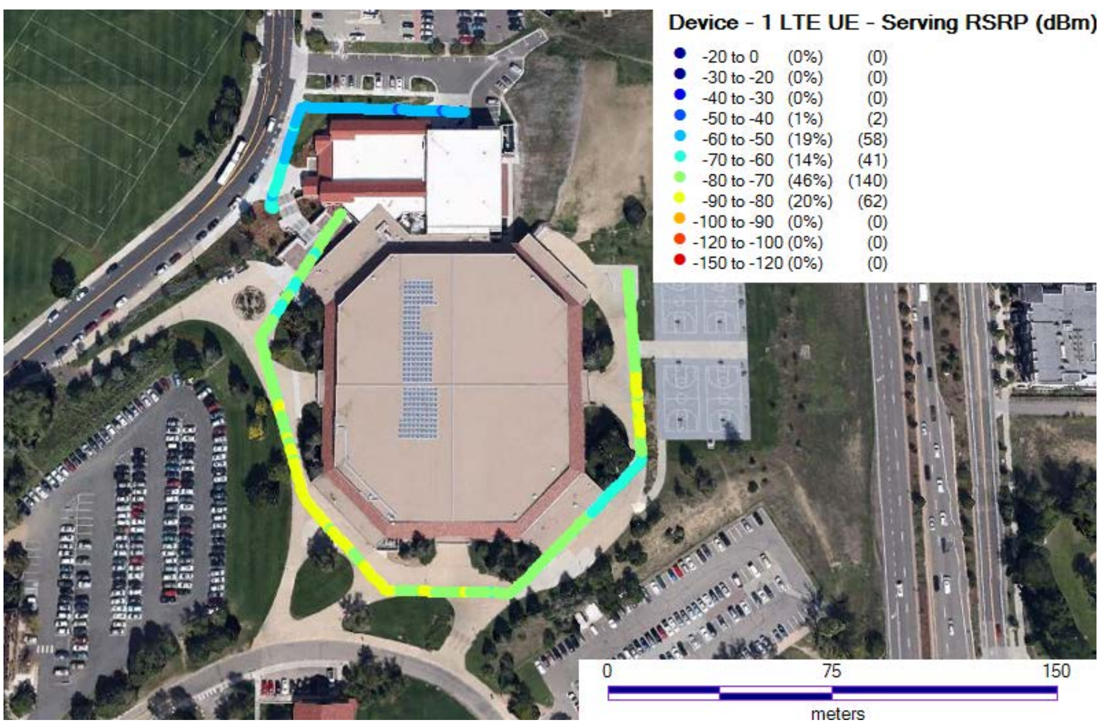

Figure 231. CEC outside (UDP downlink) reference signal received power (RSRP) with the SCDA at a transmit power of 1 W and a COW at 40 W and the PSCR MN.

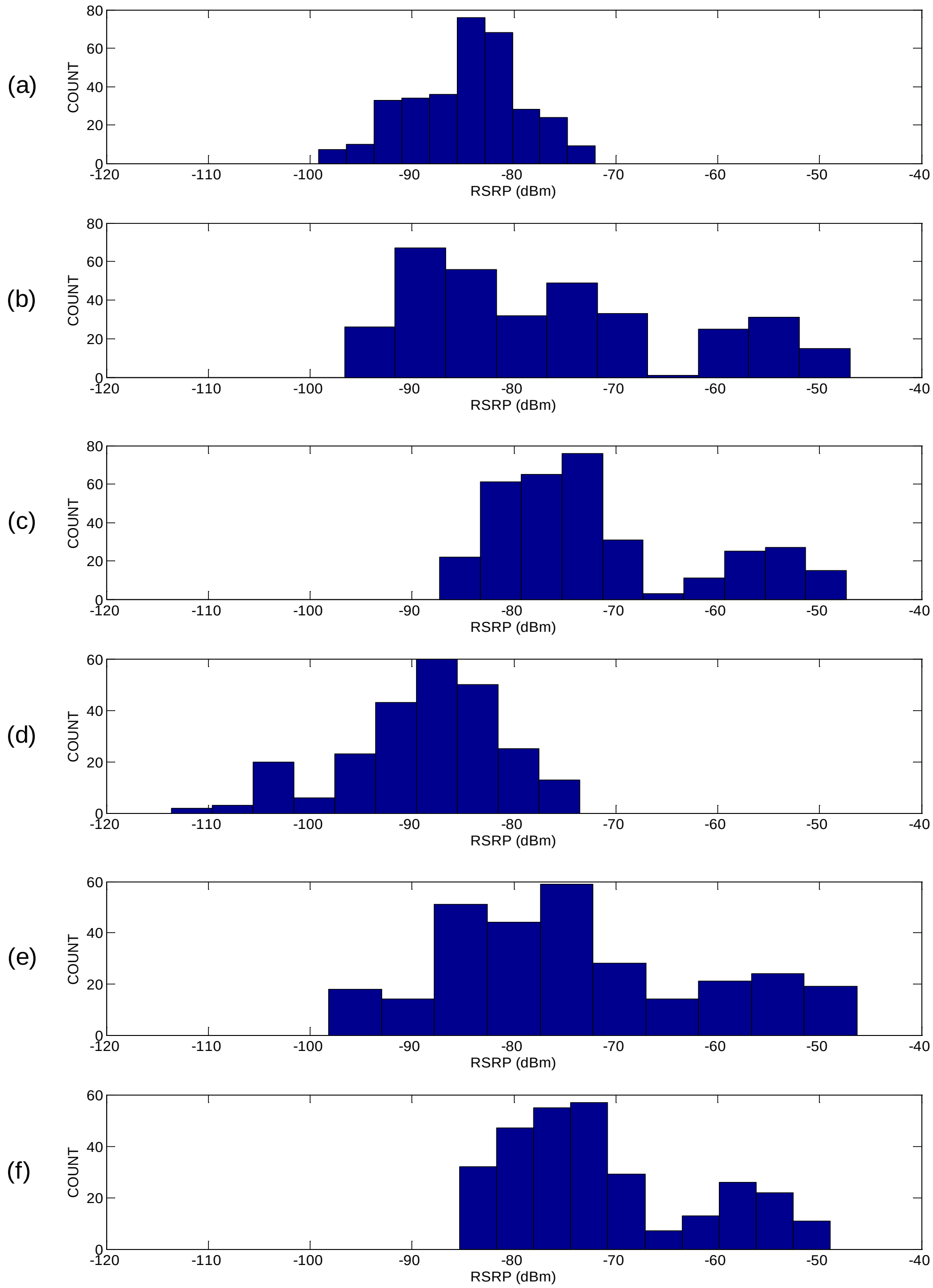

Figure 232. CEC outside histograms of RSRP for different coverage configurations with UDP downlink data flow. (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN.

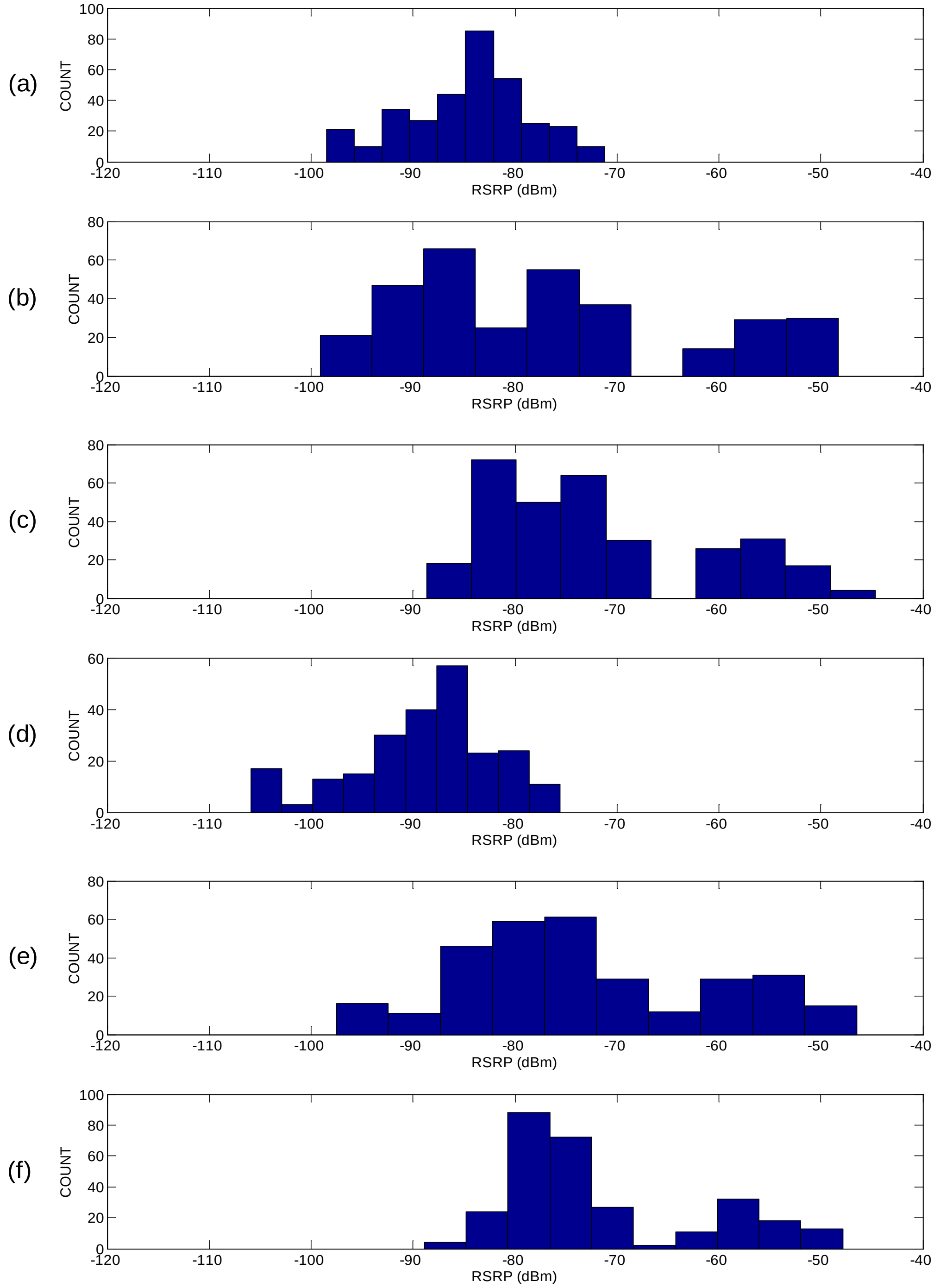

Figure 233. CEC outside histograms of RSRP for different coverage configurations with UDP uplink data flow. (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN.

Table 121. CEC outside RSRP statistics for a UDP downlink data flow.

Coverage Combination	**Mean RSRP (dBm)**	**Median RSRP (dBm)**	**Standard Deviation (dBm)**	**Min RSRP (dBm)**	**Max RSRP (dBm)**
PSCR MN	-84.6	-83.8	5.5	-99.2	-72.0
COW 40 W	-76.5	-78.6	13.2	-96.6	-47.0
PSCR MN + COW 40 W	-71.6	-74.6	10.2	-87.3	-47.4
SCDA 1 W	-88.9	-87.7	7.7	-113.6	-73.5
SCDA 1 W + COW 40 W	-74.0	-76.0	12.8	-98.2	-46.3
SCDA 1 W + COW 40 W + PSCR MN	-71.2	-73.8	9.5	-85.4	-48.9

Table 122. CEC outside RSRP statistics for a UDP uplink data flow.

Coverage Combination	**Mean RSRP (dBm)**	**Median RSRP (dBm)**	**Standard Deviation (dBm)**	**Min RSRP (dBm)**	**Max RSRP (dBm)**
PSCR MN	-84.6	-84.0	6.0	-98.5	-71.2
COW 40 W	-76.7	-78.1	13.8	-99.1	-48.3
PSCR MN + COW 40 W	-72.0	-74.7	10.7	-88.7	-44.7
SCDA 1 W	-88.9	-87.8	6.9	-105.9	-75.6
SCDA 1 W + COW 40 W	-73.2	-75.4	12.1	-97.5	-46.5
SCDA 1 W + COW 40 W + PSCR MN	-71.5	-75.3	9.8	-88.9	-47.9

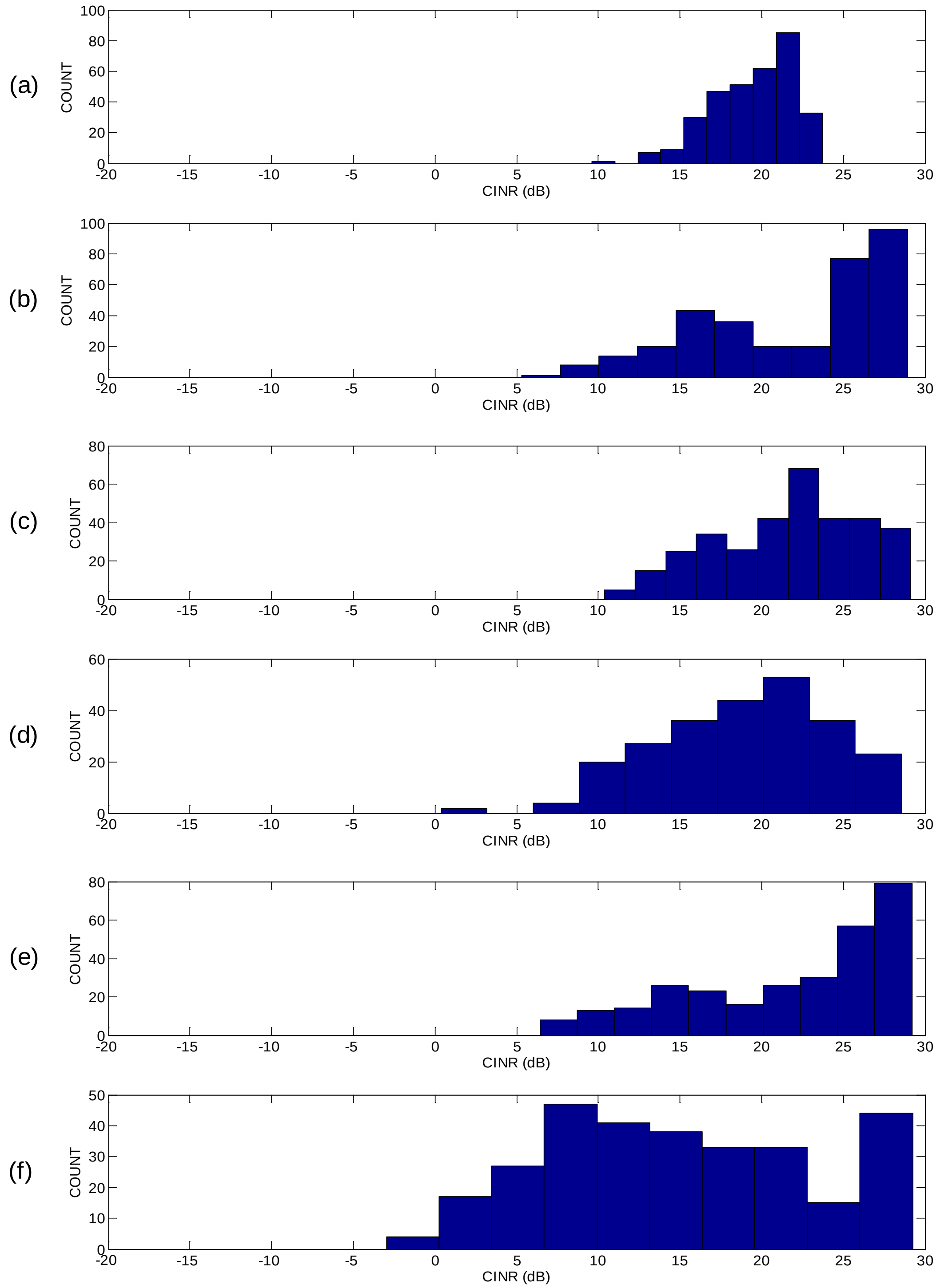

Figure 234. CEC outside histograms of CINR for different coverage configurations with UDP downlink data flow. (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN.

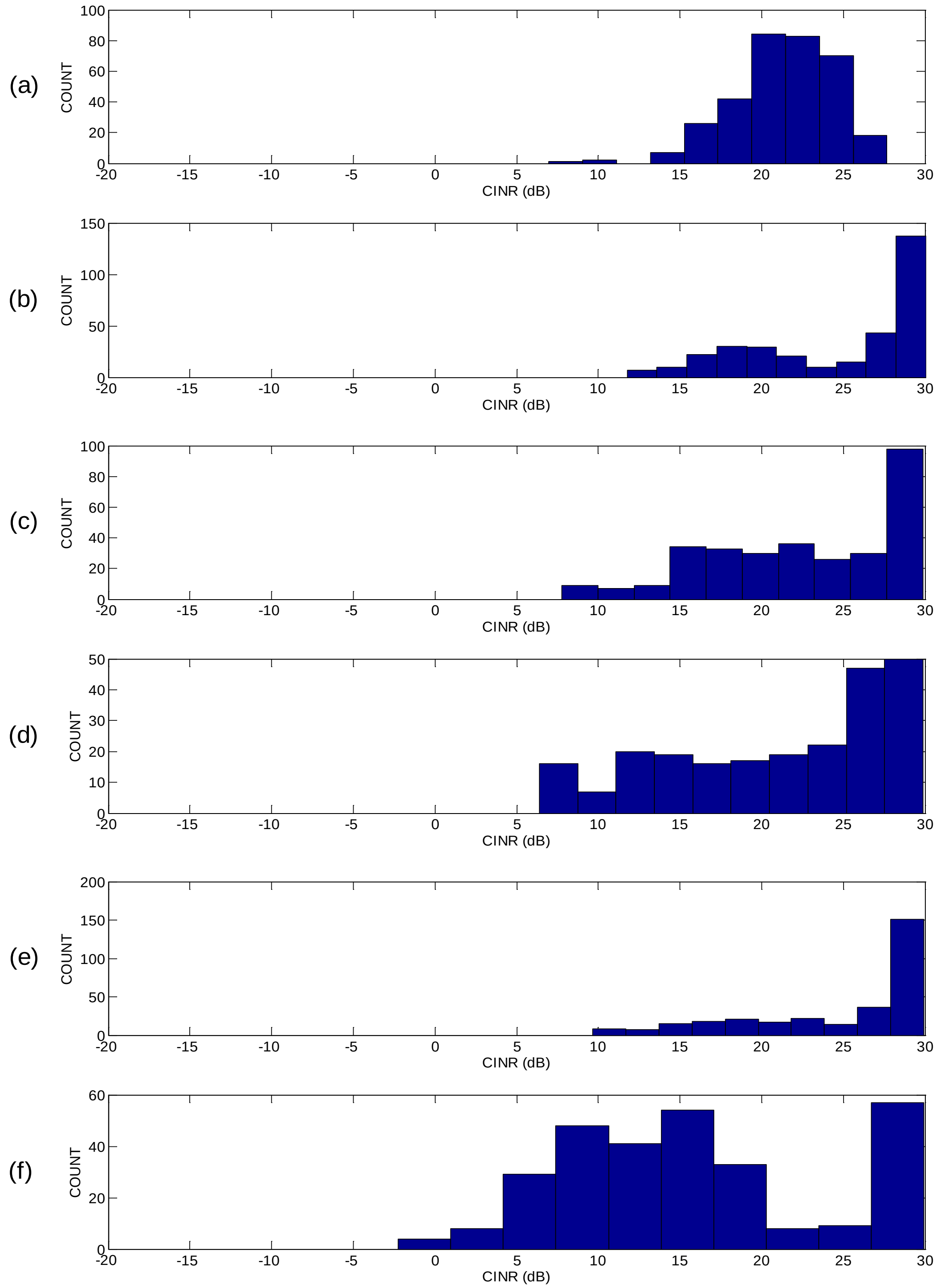

Figure 235. CEC outside histograms of CINR for different coverage configurations with UDP uplink data flow. (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN.

Table 123. CEC outside CINR statistics for a UDP downlink data flow.

Coverage Combination	Mean CINR (dB)	Median CINR (dB)	Standard Deviation (dB)	Min CINR (dB)	Max CINR (dB)
PSCR MN	19.5	19.9	2.5	9.6	23.7
COW 40 W	22.0	24.7	5.7	5.3	29.0
PSCR MN + COW 40 W	21.6	22.0	4.4	10.4	29.1
SCDA 1 W	18.9	19.4	5.3	0.4	28.6
SCDA 1 W + COW 40 W	21.8	24.2	6.2	6.4	29.2
SCDA 1 W + COW 40 W + PSCR MN	15.0	14.2	8.0	-3.0	29.3

Table 124. CEC outside CINR statistics for a UDP uplink data flow.

Coverage Combination	Mean CINR (dB)	Median CINR (dB)	Standard Deviation (dB)	Min CINR (dB)	Max CINR (dB)
PSCR MN	21.3	21.6	3.1	7.0	27.7
COW 40 W	24.5	27.5	5.2	11.8	30.0
PSCR MN + COW 40 W	22.6	23.1	5.8	7.8	29.9
SCDA 1 W	21.2	23.5	6.9	6.4	29.9
SCDA 1 W + COW 40 W	24.7	27.9	5.4	9.7	29.9
SCDA 1 W + COW 40 W + PSCR MN	15.8	14.5	8.1	-2.3	27.7

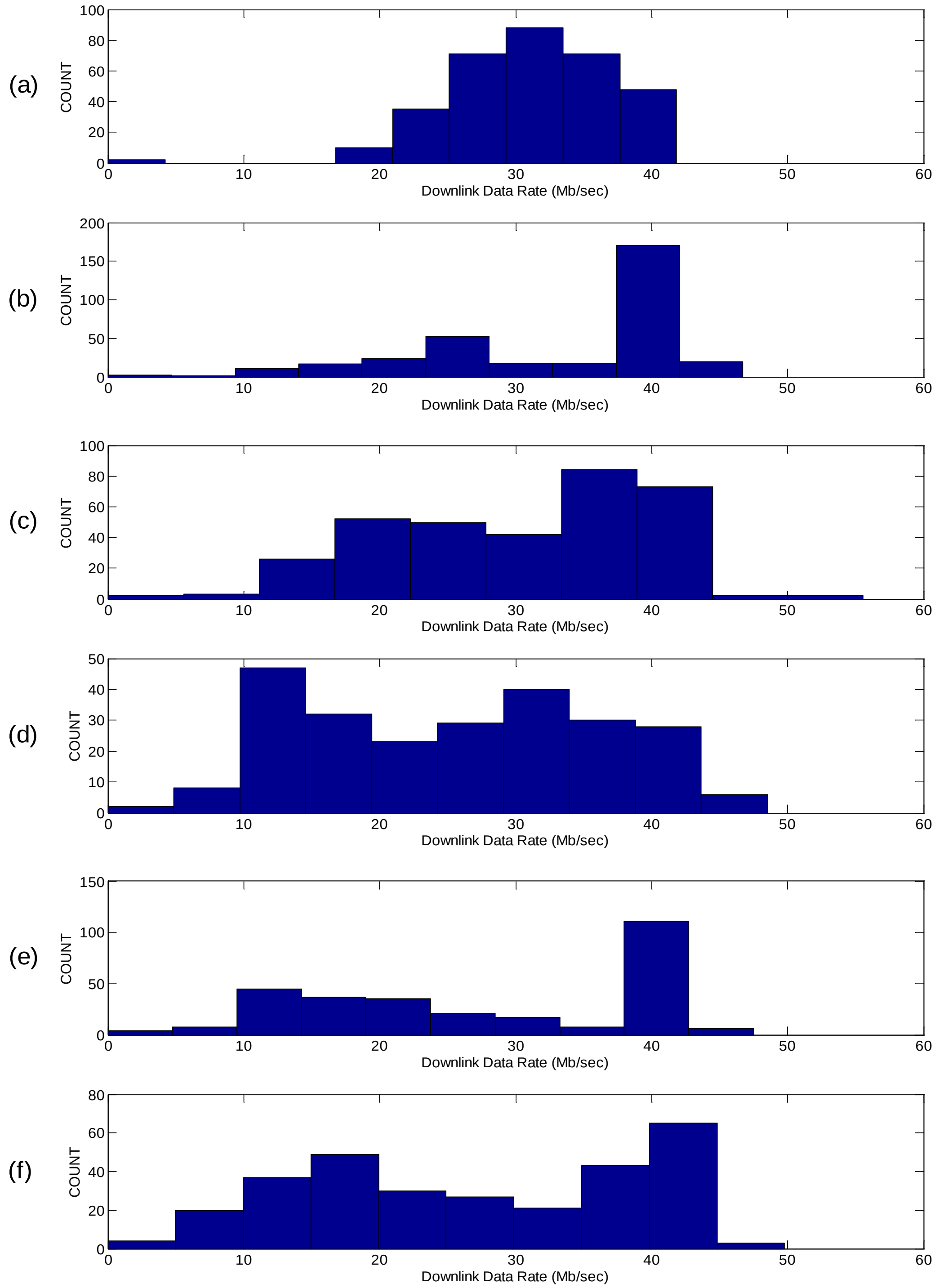

Figure 236. CEC outside histograms of PDSCH downlink data rates for different coverage configurations with a UDP downlink data flow. (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN.

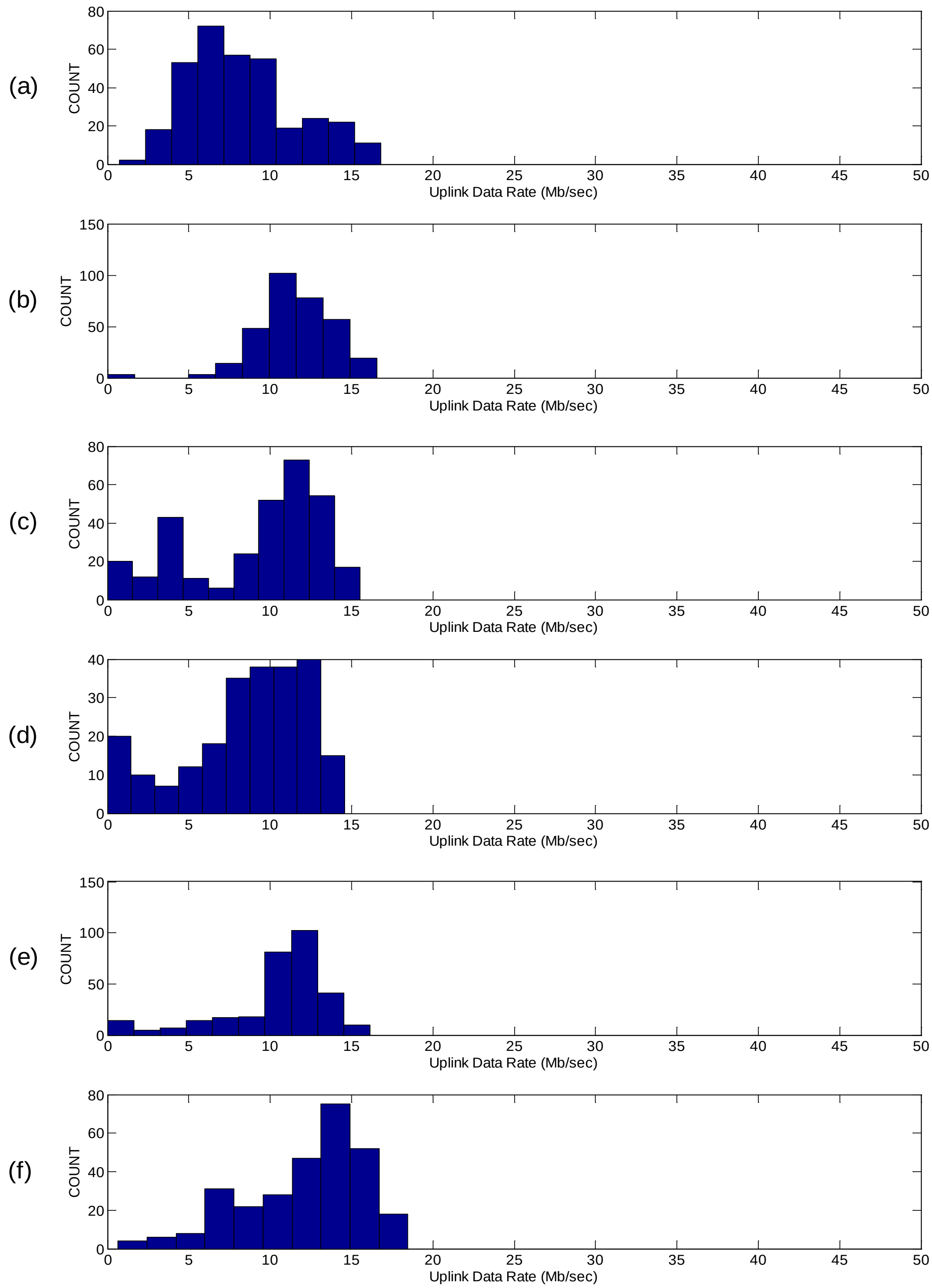

Figure 237. . CEC outside histograms of PUSCH downlink data rates for different coverage configurations with a UDP uplink data flow. (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN.

Table 125. CEC outside PDSCH statistics for a UDP downlink data flow.

Coverage Combination	**Mean PDSCH (Mb/s)**	**Median PDSCH (Mb/s)**	**Standard Deviation (Mb/s)**	**Min PDSCH (Mb/s)**	**Max PDSCH (Mb/s)**
PSCR MN	31.2	31.5	6.0	0.0	41.8
COW 40 W	33.5	39.2	9.5	0.0	46.7
PSCR MN + COW 40 W	30.4	32.7	9.5	0.0	55.6
SCDA 1 W	25.5	26.0	10.9	0.0	48.5
SCDA 1 W + COW 40 W	27.6	27.6	12.4	0.0	47.5
SCDA 1 W + COW 40 W + PSCR MN	26.5	26.5	11.9	0.0	49.8

Table 126. CEC outside PUSCH statistics for a UDP uplink data flow.

Coverage Combination	**Mean PUSCH (Mb/s)**	**Median PUSCH (Mb/s)**	**Standard Deviation (Mb/s)**	**Min PUSCH (Mb/s)**	**Max PUSCH (Mb/s)**
PSCR MN	8.3	7.7	3.4	0.7	16.8
COW 40 W	11.5	11.5	2.3	0.0	16.6
PSCR MN + COW 40 W	9.1	10.5	4.2	0.0	15.5
SCDA 1 W	8.6	9.2	3.8	0.0	14.6
SCDA 1 W + COW 40 W	10.4	11.3	3.3	0.0	16.1
SCDA 1 W + COW 40 W + PSCR MN	12.1	13.0	3.7	0.7	18.5

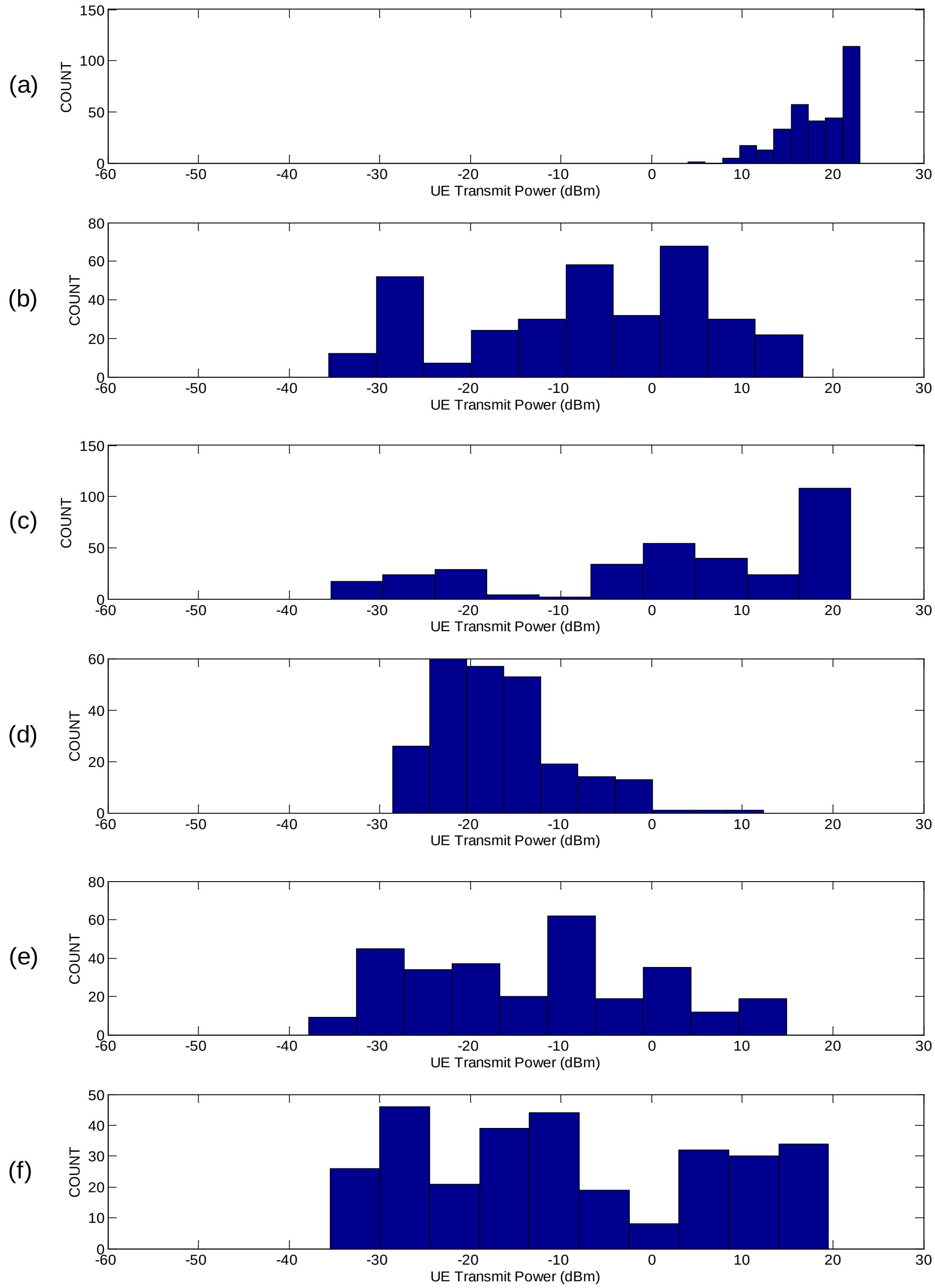

Figure 238. CEC outside histograms of UE transmit power for different coverage configurations with UDP downlink data flow. (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN.

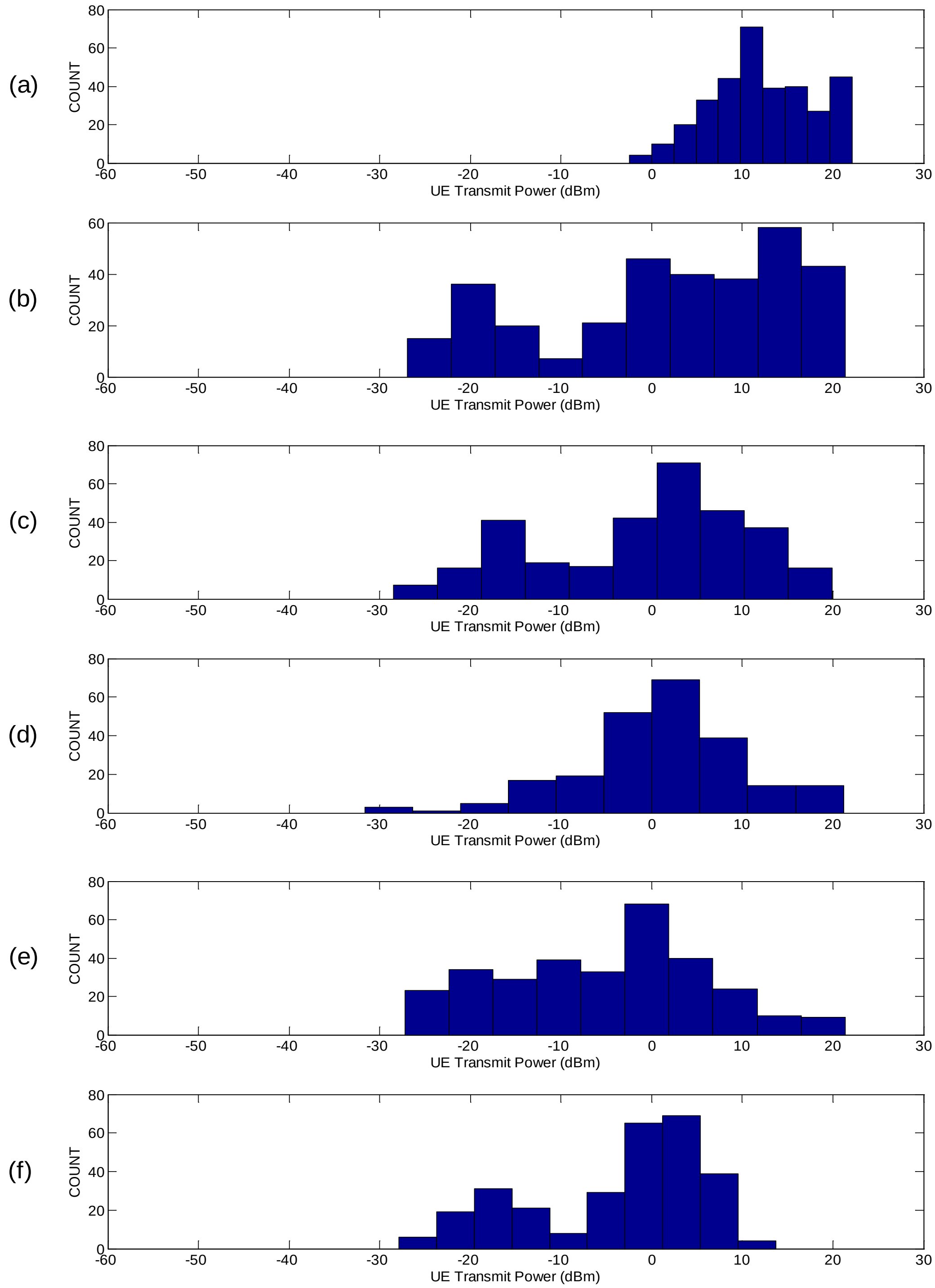

Figure 239. CEC outside histograms of UE transmit power for different coverage configurations with UDP uplink data flow. (a) PSCR MN, (b) COW at 40 W, (c) COW at 40 W and PSCR MN, (d) SCDA at 1 W, (e) SCDA at 1 W and COW at 40 W. (f) SCDA at 1 W, COW at 40 W, and PSCR MN.

Table 127. CEC outside UE transmit power statistics for a UDP downlink data flow.

Coverage Combination	**Mean UE xmit (dBm)**	**Median UE xmit (dBm)**	**Standard Deviation (dBm)**	**Min UE xmit (dBm)**	**Max UE xmit (dBm)**
PSCR MN	18.3	19.1	3.7	4.0	23.0
COW 40 W	-7.0	-5.6	13.5	-35.6	16.7
PSCR MN + COW 40 W	2.6	5.2	17.1	-35.4	22.0
SCDA 1 W	-16.8	-17.9	6.9	-28.6	12.4
SCDA 1 W + COW 40 W	-12.8	-11.1	13.3	-37.8	14.9
SCDA 1 W + COW 40 W + PSCR MN	-9.1	-11.2	16.1	-35.5	19.5

Table 128. CEC outside UE transmit power statistics for a UDP uplink data flow.

Coverage Combination	**Mean UE xmit (dBm)**	**Median UE xmit (dBm)**	**Standard Deviation (dBm)**	**Min UE xmit (dBm)**	**Max UE xmit (dBm)**
PSCR MN	12.3	11.7	5.6	-2.5	22.1
COW 40 W	1.8	3.4	13.8	-26.9	21.4
PSCR MN + COW 40 W	-0.9	1.4	11.4	-28.5	20.0
SCDA 1 W	1.1	1.4	9.1	-31.6	21.1
SCDA 1 W + COW 40 W	-5.0	-3.1	11.3	-27.2	21.4
SCDA 1 W + COW 40 W + PSCR MN	-3.8	-1.4	9.6	-27.9	13.7

6. SUMMARY AND CONCLUSIONS

The report describes measurement campaigns that were conducted on the campus of the University of Colorado at Boulder at the Discovery Learning Center (DLC) and the Coors Event Center (CEC). Both structures are located well within the coverage area of the PSCR Band 14 macro network (MN) which makes them well suited for investigation of in-building coverage of public safety Band 14 LTE networks. We used the macro network coverage as a baseline to study methods for improving indoor coverage. We investigated three approaches for coverage improvement at the DLC: 1) a cell on wheels (COW) placed in close proximity to the DLC, 2) a small cell feeding discrete antennas (SCDA) placed inside the DLC, and 3) a small cell feeding a distributed antenna system (SCDAS) installed on the ground floor. At the CEC, we did not deploy the SCDAS, and we used an SCDA inside the stadium of the CEC and a COW placed in an adjacent parking lot as additional coverage elements.

Our test results indicate that the PSCR MN did not provide complete coverage of either the DLC or the CEC. We did see a significant improvement in indoor coverage and system performance when we used either a small cell or COW individually or in combination with the PSCR MN. Our findings indicate that the PSCR MN does not provide complete indoor coverage and that some form of in-building support is needed to achieve a high level of LTE performance inside either the DLC or the CEC.

We have obtained an extensive set of data for selected LTE parameters. The behavior of these parameters as a function of the in-building coverage configuration is quite complex. More research is clearly needed to further explore performance improvement of in-building public safety LTE systems.

One area that we were not able to cover in this study was the optimal control of handovers between eNBs when multiple elements were used to provide coverage. The tight time constraints of our field tests precluded optimization, but the results demonstrate that simply increasing RF coverage does not necessarily lead to higher data rates. Peak performance requires both adequate coverage and handover optimization.

Another area that should be explored is the repeatability and associated uncertainties of in-building measurements. One question that naturally arises in this context is how can we accurately quantify in-building coverage? This is a difficult question considering that we cannot perform walk tests through all the spaces in a building. In the case of the DLC and the CEC we were relegated to testing in the main public thoroughfares such as hallways and the stadium—we did not have access to most of the lab and office spaces. Another question that naturally arises is: if we can only perform measurements over a limited portion of a building, how reliably can we predict coverage? This is a challenging problem, indeed, and it will require a combination of additional measurements, analysis, and electromagnetic simulations. There is much work to be done.

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